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STATUS AND PLANS OF THE UNITED STATES AND CERN HIGH ENERGY PHYSICS PROGRAMS AND THE SUPERCONDUCTING SUPER COLLIDER [SSC]

HEARING

BEFORE THE

SUBCOMMITTEE ON
ENERGY DEVELOPMENT AND APPLICATIONS

OF THE

COMMITTEE ON
SCIENCE AND TECHNOLOGY
HOUSE OF REPRESENTATIVES

NINETY-NINTH CONGRESS

FIRST SESSION

OCTOBER 29, 1985

[No. 64]

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Committee on Science and Technology

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STATUS AND PLANS OF THE UNITED STATES AND CERN HIGH ENERGY PHYSICS PROGRAMS AND THE SUPERCONDUCTING SUPER COLLIDER [SSC]

TUESDAY, OCTOBER 29, 1985

House of Representatives,
Committee on Science and Technology,
Subcommittee on Energy Development and Applications,
Washington, DC.

The subcommittee met, pursuant to notice, at 2 p.m., in room 2325, Rayburn House Office Building, Hon. Don Fuqua (chairman of the subcommittee) presiding.

Mr. Fuqua. Today's hearing will consider the status and plans of the United States and CERN high energy physics programs and the superconducting super collider, also known as the SSC.

It has now been 2 years since the Department of Energy initiated an R&D Program on the SSC, a multibillion dollar scientific research facility for the study of the fundamental nature of matter. The SSC activities to date have been provided a total of approximately $40 million, and an additional $20 million has been appropriated for fiscal year 1986.

The SSC Program's most recent accomplishment was last month's selection of the SSC magnet style, which determined the circumference of the machine to be approximately 60 miles. In light of this important milestone, the subcommittee thought it an appropriate time to review the accomplishments of the SSC Program to date and to consider the program's next step.

We're pleased today to have Dr. Trivelpiece and Dr. Tigner, the Directors of the DOE Office of Energy Research and the SSC Central Design Group, respectively, to review the accomplishments and near-term plans. We are also pleased that the chairman and several members of the SSC Magnet Selection Advisory Panel, as well as representatives of the Texas Accelerator Center, are with us to review the magnet selection process.

In addition to the SSC activities, the U.S. high energy physics community has been rethinking our national program in light of the desire to build the SSC by the mid-1990's. During this period of April to July 1985, the High Energy Physics Advisory Panel, chaired by Dr. Jack Sandweiss of Yale University, conducted an in-depth review of United States, European, and Japanese high energy physics programs. Professor Sandweiss will be sharing the recommendations of this study with us.

High energy physics is international in scope and it would be inappropriate to consider the U.S. program in isolation. Certainly some of the most exciting results in the field in recent years has come from CERN, the European Laboratory for Elementary Particle Physics. CERN is also constructing the largest accelerator to date, the LEP electron-positron collider with a circumference in excess of 16 miles.

A plausible alternative to the SSC is a lower energy, lower cost large hadron collider, which would be constructed in the LEP tunnel and could provide a collision energy in the range of one-quarter to nearly one-half that of the SSC depending upon the magnet configuration.

We are honored that Dr. Schopper, the Director General of CERN, and Dr. Carlo Rubbia, chairman of the Working Group on the Scientific and Technological Future of CERN, can be with us today to discuss the current status and future plans for CERN.

The purpose of today's hearing is not to debate whether or not the SSC should be built, that's for another time. Rather, the purpose is to gauge the progress that has been made to date and to consider the possible alternatives to the SSC. I believe that everyone here is aware of my concern and the committee's concern about the cost of the SSC. And I also believe that the message put forth by the late physicist Werner Heisenberg, in an article in the February 1973 issue of Science, bears repeating. He said:

> In expounding the reasons for or against such a project it is important to put the burden of proof where it belongs . . . the proponent of such a project is the one to bring proof of its urgency, of the results expected of it.
>
> It is not up to the opponent to prove that a scientific project breaking new ground will not produce startling and important new discoveries. But this alone can never provide sufficient reason for spending billions. Hence, a burden of proof must definitely lie with those who claim such extremely large public funds.

Our first witness today will be Dr. Alvin Trivelpiece, the Director of the Department of Energy's Office of Energy Research. And just prior to that, I might say without objection, permission will be granted to use cameras and recording during the course of the hearing. And because of the time constraints and the House being in session, I would like to ask our witnesses if we could limit their statements to no more than 10 minutes, in order to provide the opportunity for the Members to respond with questions regarding that.

And at this time I would like to ask if Mr. Barton has a statement that he wishes to make.

Mr. Barton. Thank you, Mr. Chairman. I do have an opening statement. I'd like to thank you for taking the initiative to call this very important hearing on the superconducting super collider. I feel that it's very appropriate that we examine the progress of the SSC to this point and determine where to go.

I strongly support the goals of the SSC project. The research which will be conducted under the SSC will ensure that this country retains its lead in basic high energy physics research. Furthermore, the SSC has spinoffs which are only now being fully realized. From medicine to military weaponry, there are countless fields which will benefit from the SSC research.

At the same time, however, I am very concerned, as you are, about the extremely high cost of this project. The Department of Energy has estimated that it will cost between $4 to $6 billion to build and equip the superconducting collider. This does not include the hundreds of millions of dollars it will cost to run the facility each year. The prospects for congressional approval of a $6 billion science project are certainly slim. Even members of the high energy physics community are hesitant to back the project at this high cost.

At a time of great concern about the budget deficit, we must go the extra mile to ensure that each Federal dollar is spent in the most efficient manner. Every effort must be made to minimize costs in all areas of this project. I am looking forward to hearing each witness comment on not only the scientific desirability of the superconducting collider, but also the most cost-effective approach to use.

Thank you, Mr. Chairman.

Mr. FUQUA. Mr. Stallings.

Mr. STALLINGS. Thank you, Mr. Chairman. I also concur that this is a very appropriate hearing. I think that this is something that the scientific community in this country as well as the world is really looking to. I do have an opening statement I would like to make.

A major initiative proposed by the high energy physics community to the Department of Energy is the construction of the superconducting super collider. This important facility would be a world center for high energy physics and help assure that America maintains its leadership role in the frontiers of science.

With the rapid advances that have been made in both particle physics and accelerator technology, it is time that we move ahead in the development of this field with the construction of the SSC. A working partnership and coordinated national effort between the Federal Government, our universities and private industry is critical to the success of this program.

Although no decision has been made to proceed with the construction of the SSC, it is important to note that several critical issues have been resolved, and that a site selection process has been established by the Department of Energy.

After 2 years of research, development, and testing, I am pleased that a preferred magnet type has been selected. Selection of the magnet is a major step in completing plans for the overall design of the SSC. In addition to the magnet selection, a site criteria document has been submitted to the Department of Energy outlining the physical, technical, and demographic requirements for the SSC site.

It is important now that DOE issue site proposal invitations so that the interested parties can submit their respective proposals. Next year, the State of Idaho will submit a formal proposal to the Department of Energy for consideration in the site selection process. The expertise of our DOE laboratories, such as the Idaho National Engineering Lab, can and should play a major role in this exciting field. Regardless of the site selection, it is imperative that a national commitment be made regarding the SSC. Without strong support from the administration and Congress, its future is in doubt.

At this time I would also like to recognize and welcome to this hearing Mr. Rick Tremblay, the Idaho SSC Coordinator.

This hearing today focuses on a program of international importance and offers both a great opportunity and challenge to the science and technology community. I commend you, Mr. Chairman, for holding this hearing and I'm looking forward to the testimony from our distinguished panel of witnesses.

Mr. **Fuqua**. Dr. Trivelpiece, we'll be pleased to hear from you.

Dr. **Trivelpiece**. Mr. Chairman, members of the subcommittee, it's a pleasure to be here today. I hope that my prepared statement can be accepted into the record.

Mr. **Fuqua**. Yes; it will be made part of the record.

Dr. **Trivelpiece**. Thank you.

STATEMENT OF DR. ALVIN W. TRIVELPIECE, DIRECTOR, OFFICE OF ENERGY RESEARCH, U.S. DEPARTMENT OF ENERGY, WASHINGTON, DC

Dr. **Trivelpiece**. You are about to hear from an array of experts here on this subject, and I'm not going to try to preempt the remarks that they're going to make. High energy physics is an important activity to the country, and certainly DOE is one of the supporters of it.

The funds for high energy physics from 1982 have grown from about $360 million to the present 1986 budget of $520 million. There have been some major upgrades in the high energy physics program activities: the Stanford linear collider, a $115 million project, that activity has extended its capability and given it new activities to do; the Fermi Laboratory, the Energy Saver, which is the first superconducting high energy physics accelerator anywhere, is the first superconducting accelerator that has been built. And attached to it are two projects, Tevatron I and Tevatron II. Tevatron II involves the fixed target activities of one tera-electron volt, and the TeV I is the one TeV on one TeV collider. That was operated for the first time only a few weeks ago at an energy of 1.6 TeV.

The day before that happened, Secretary Herrington had the opportunity to visit the laboratory and tour the facilities, and participate in a dedication ceremony. He was pleased to do it and was very impressed with what went on. So some of these things are in part—part of the good news. One of the pieces of unfortunate news was the Isabelle project which was terminated a couple of years ago. And as you indicated, we did have hearings on that subject. And at that hearing we informed you of our decision to terminate, and some $20 million of 1984 funds were reprogrammed into that activity. That was followed by $20 million last year and we're at $20 million for this year.

Those funds have been used, as has been indicated, in part for some of these things which involve the establishment of a Central Design Group at Berkeley, which is headed by Maury Tigner, and you're going to hear from him later.

The activity that they undertook first was the reference designs study. That reference designs study indicated that of the three magnet choices, the high field, the medium field to low field, that the cost was approximately the same in each case because in one case the cost of the magnets was offset by the amount of real estate that would be needed in which to put them. And surprisingly the cost came out approximately $4 billion in 1984 dollars. And if you escalated that over the life of the project, it was likely to be about $6 billion.

A site parameters document was prepared, and we do have it. I did send letters to all the Governors indicating that we had that. And that was in part our attempt to try to make sure that if, inadvertently or intentionally, some bias had been built into that, which some region or locale might decide made an unfair bias in favor or against them, that they could inform us of that. We have not issued it formally, and there are reasons for that.

The plan had been from the outset to select one magnet type and use it for further prototype development. That choice has been made. I believe that to be a site independent choice. And one of the reasons for doing additional prototype development was that in that reference design study, certain assumptions were made regarding the benefits for cost-reducing design assumptions. And those need to be verified, and that's what part of the project would be from here on out.

We did attempt also to try to create an early notice of what would be a fair and objective process by which site selection would take place. We prepared a collection of letters that were sent to the president of the Academy of Sciences and the Academy of Engineering, asking for their assistance at some point if the Department decides to proceed and the Congress approved.

I would like to stress, however, that no decision has been made to proceed with the construction. It is not any particular secret at this point that it is not in the 1987 budget, but funds are going to be requested to continue the activities that are now going on.

Over the next few months I plan to brief Secretary Herrington on various aspects of the SSC project, not necessarily with the expectation that it would be in the 1988 budget, but it is the first possible budget in which we believe it could be given consideration.

I would remind everyone that even if it is in the 1988 budget, that the earliest time that hearings would take place on that would be the spring of 1987. And the Department would not propose to proceed until such time as hearings had been held. And prior to that it does take a Secretarial agreement to include this in the budget, and an object of this size and scope would require Presidential endorsement of it.

So, the earliest we could conceive of would be the spring of 1987, and sometime subsequent to that then the Department, if it were to proceed, would ask for RFP's for this and there would be a process that I can't see taking less than 1½ or 2 years before such time as a site selection could be made.

I know people are eager to get on with this, but there are certain realities of the budgetary decision—process that do have to be taken into account.

This is a very important project, and I think it is important to proceed in a satisfactory manner. It has my support, and we are trying to do what we can to ensure that the necessary information is made available to the Secretary so that he can review it in connection with some future budget activity.

Mr. Chairman, that concludes my remarks. I'd be pleased to answer any questions.

[The prepared statement of Mr. Trivelpiece follows:]

Statement of Alvin W. Trivelpiece
Director
Office of Energy Research
Department of Energy
before the
Subcommittee on Energy Development and Application
of the
House Science and Technology Committee
October 29, 1985

Dear Mr. Chairman and Members of the Subcommittee:

It is a pleasure to appear before the Committee this afternoon at this special hearing devoted to the Status and Plans of the U.S. and CERN high energy physics programs and the Superconducting Super Collider (SSC). High energy physics is a basic science that explores the fundamental nature of matter and energy. The Department of Energy is pleased to be able to provide the principal support for the U.S. high energy physics program.

Good progress has been achieved in recent years in improved understanding of the fundamental constituents of matter and the basic forces that influence their behavior. The "Standard Model" now provides a framework within which these things can be viewed consistently. This Model incorporates three of the four basic forces in nature and includes a picture of matter as composed of various combinations of a relatively small set of basic constituents, called quarks and leptons.

However, many of the predictions of the Standard Model have not been verified, and it is probably not the final answer. Questions such as the origin of particle masses cannot be answered within the theory. There is much left to do.

Experiments in high energy physics involve the use of beams produced by particle accelerators. The DOE-supported U.S. facilities include the Fermilab facility which operates at 800 GeV for fixed-target experiments; the SLAC facilities, which include capabilities for fixed-target experiments with beams of 32 GeV electrons from the Linac, the 4 GeV on 4 GeV SPEAR electron-positron colliding beam facility, and the 15 GeV on 15 GeV PEP colliding beam facility; and the Alternating Gradient Synchrotron (AGS) proton synchrotron at Brookhaven National Laboratory (BNL) which provides 30 GeV protons and 16 GeV polarized protons for fixed-target experiments. In addition, the National Science Foundation supports the 8 GeV on 8 GeV Cornell Electron-Positron Storage Ring (CESR).

A set of upgrades to existing facilities is now nearing completion. At Fermilab, the first step of this program was completed in 1983. This involved the fabrication and installation of nearly 1000 superconducting magnets in the main ring tunnel to raise the energy capability of the accelerator to near 1000 GeV, and at the same time, reduce electric power requirements. The superconducting magnet ring has been operating for physics research at energies up to 800 GeV for over two years. The remaining phase of this Tevatron program includes completion of the upgrade of fixed-target beams and experimental facilities to permit experiments with the higher energy secondary beams made possible by 1000 GeV protons; and the provision of an antiproton source and experimental facilities to permit study of collisions of 1000 GeV protons with 1000 GeV antiprotons. I am pleased to report that Fermilab earlier this month passed a major milestone in the testing of the Tevatron colliding beam phase with the achievement of proton-antiproton collisions at 800 GeV on 800 GeV. Both the fixed-target and colliding beam phases of the Tevatron are progressing well and should be fully operational by FY 1987.

At SLAC, the Stanford Linear Collider (SLC) is being constructed as a significant upgrade of the SLAC Linac. One purpose of the SLC is to explore the technical feasibility of a new concept for electron-positron colliders. SLC will give U.S. physicists early access to the important and exciting physics made possible by copious production of Z^0 particles, which were recently discovered at CERN. SLC construction is proceeding well and tests of the 50 GeV on 50 GeV collider are to begin about a year from now.

I believe that the U.S. high energy physics program is healthy today. The facility upgrades in progress at Fermilab and SLAC will provide two world forefront research capabilities into the next decade of the 1990s.

Although these upgrades will permit exploration in new physical domains and exciting new discoveries, they cannot permit exploration of the TeV mass scale where breakthroughs in understanding and new phenomena are anticipated. For example, the Standard Model predicts the existence of a new quantum field, the Higgs field, whose confirmation is crucial to understanding the nature of matter and energy. Access to the TeV mass scale will definitely test this key feature of the Standard Model, and in this entirely new domain never before explored. Thus, by the mid-1990s a new facility with the capability to explore the TeV mass scale will be required if the U.S. high energy physics program is to remain at the research forefront. Because of the long lead time involved, preparation for capabilities for the mid-1990s is already under way.

This brings me to the SSC, which has been the subject of great interest, both in the scientific realm and in the public realm. I would now like to state where we've been, what we are committed to, and where we may be going with the SSC.

The SSC as proposed by the high energy physics community has their strong support. It would be an important scientific facility. As presently envisaged, it would be large and expensive compared with existing accelerator facilities. We are funding a limited R&D program that will carefully assess costs, examine cost-reduction opportunities, and resolve technical and design issues. This program will provide crucial input upon which to base an informed judgment about proceeding with the SSC at an appropriate time.

Let me begin to elaborate by briefly reviewing the history of the activity. In late 1983, the Department developed a plan to initiate preliminary R&D related to the SSC. This plan was discussed at the October 19, 1983, hearing before this Committee. The activities begun in FY 1984 have been continued into FY 1985 and FY 1986. As yet, I cannot comment specifically on next year's plans, but generally I expect a continuation of the present activities.

There is a coordinated national R&D effort drawing on the resources and expertise of DOE laboratories, universities, and industry. Capable leadership for the national effort has been provided by the SSC Central

Design Group. The technical progress of the R&D activities has been excellent. All critical milestones have been met. I will mention a few. The first was the Reference Designs Study (RDS) carried out in early 1984. This Study established the technical feasibility of the SSC, developed a realistic preliminary cost estimate based on clearly defined, credible assumptions about R&D accomplishments which could be achieved, and identified key R&D questions to be pursued. The RDS was extensively reviewed by DOE including my staff in Energy Research, the Independent Cost Estimating Staff of the Assistant Secretary for Management and Administration, and numerous technical consultants. The RDS is the basis for the SSC cost estimates which are often quoted. Since there is some confusion in the way these estimates are used, I would like to go step by step through the numbers.

The RDS established an estimate of $3 billion in FY 1984 dollars for construction costs. When the costs of R&D, detectors, and preoperations are added, the total cost associated with the SSC becomes $4 billion. When the $4 billion is escalated to then year dollars over an assumed construction schedule of six to seven years, the total cost becomes about $6 billion. The costs of land acquisition are excluded from these estimates since it is assumed that the site will be provided without cost to the federal government.

I am pleased to report that the R&D conducted in the ensuing year or so has confirmed the R&D assumptions of the RDS, and in a number of critical cases, expectations have been exceeded. I am also happy to report that revised cost estimates developed in the summer of 1985 show that the cost estimates of the RDS are still valid and, in fact, costs may have come down some.

Until recently, the magnet R&D program has focused on examining a number of technical options, to provide a basis for deciding which magnet type would lead to the most cost-effective and operationally reliable SSC. Recently a decision was made with regard to a particular high field magnet design for further prototype work. I reviewed the decision and the method used in arriving at the selection of this magnet type, and concluded that the CDG established and followed a sound procedure.

With this decision made, the R&D and design studies can now focus on optimizing the design of the chosen magnet type and on developing a conceptual design and a comprehensive cost estimate for the full facility. In order to most effectively transfer advanced technology to industry and take full advantage of industrial expertise, it is important that industry directly participate in R&D and design activities early in these efforts. Cost-effective assembly features are best built into the design at an early date and should be addressed now.

It is anticipated that a conceptual design report and a comprehensive cost estimate will be received from the Central Design Group by April 1, 1986. This will be thoroughly reviewed by the Department, including all aspects--scientific, technical, schedule, and cost. The results of the R&D program, together with these reviews, will provide the Department with much of the information necessary for a decision on the future direction of SSC activities. I can make no commitment or prediction at this time on behalf of the Department about whether a decision concerning construction will be made in the FY 1988 budget process or obviously what that decision might be. Any decision to proceed with construction would have to be made with the full support of the Secretary.

I am aware that there is concern among scientists in fields of science other than high energy physics that the SSC will adversely impact their fields. I see no reason why this need be. In attempting to maintain the health and productivity of high energy physics, care must be taken so that other important elements of U.S. basic science do not suffer adversely.

I would like to turn now to the question of international cooperation in the SSC project. As you are well aware, high energy physics has a long history of extensive, effective, and mutually beneficial international cooperation.

We are actively pursuing the possibilities for international collaboration and cost sharing in the SSC. I have had specific discussions with the Japanese and Western Europeans; however, it is too early to determine the possibilities for collaboration. Until such time as our own plans are clear, it is not possible to go much beyond the hypothetical stage. Even so, there are encouraging signals.

If international collaboration is to succeed, it is imperative that the flexibility to negotiate a suitable agreement be maintained. Any premature requirements for specific levels or conditions would likely make it impossible to conclude satisfactory agreements.

It is understandable that there is great interest in the siting of the SSC. I want to stress again that the Department has made no decision either to proceed with the SSC or to issue an invitation for site proposals.

In view of the great interest in siting, however, the Department issued a press release in December 1984, outlining the site selection process it would plan to follow at an appropriate time. This was done simply to let all interested parties know that we planned a fully open, competitive site selection process and to make sure that information was equally available to all. In April 1985, the SSC Central Design Group prepared a technical advisory on site criteria for the Department. We subsequently notified all the governors that the report was available from CDG. These are the only actions that the Department has taken in the site arena. There is, at this time, no Departmental commitment or time schedule for a site proposal invitation.

I hope this helps clarify the situation relative to the SSC. The scientific potential and importance of the SSC to the U.S. program in high energy physics is clear, and we are committed to carefully examine cost and design issues that will allow the Secretary to make an informed decision on whether or not to proceed.

Mr. Chairman, that concludes my formal presentation. I will be happy to respond to any questions you might have.

Mr. FUQUA. Thank you, Dr. Trivelpiece.

DISCUSSION

You indicated that the SSC project will continue at about $20 illion per year in 1986 and 1987?

Dr. TRIVELPIECE. Well, I didn't indicate what the 1987 budget umber is going to be. We haven't received our passback from MB yet, so I don't know. And even if I did, I could not reveal it at his juncture.

Mr. FUQUA. I understand. But assuming it's coming at somehere in that level——

Dr. TRIVELPIECE. The intent is to continue with the present colction of activities.

Mr. FUQUA. At what time—what if a decision was made not to roceed with the SSC? Would—do you have any idea how long that ight be, or when a final decision might be made if 1988 is a crital year?

Dr. TRIVELPIECE. Well, I don't believe that sufficient information available yet in terms of some questions that need to be anvered to make the case to the Secretary. How he would handle it om that point on, I have no way of knowing at this point.

I don't think we're proceeding along a path which assumes that e're not going to do this. So, we really haven't crossed the what if ot question.

Mr. FUQUA. You mentioned in your statement—I think it's on ge 3, but it's immaterial and you do not have to refer to it—we d some hearings about a year or so ago, I think, with some of the rectors in the high energy physics field. And I remember SLAC ing here and some of the others. And a question came up about e percentage of operating time that they were getting because of e escalation in energy prices.

It's my understanding that SLAC right now, and I imagine the hers are facing similar things where energy prices are escalating d they're not able to operate at the levels that they were before. ow, I've forgotten the percentages, but it seems like it was not a ry high percentage that they were able to operate because—one the reasons—of operating costs.

Questions have been posed to me by other people that said why ild something else when you can't even operate what you have full capacity.

Dr. TRIVELPIECE. That is a difficult—it is indeed true that the ergy costs have squeezed the operating budgets at several laboraies, and in some cases we are probably not operating in some of facilities that we are responsible for at a level that is consistent h the investment that's been made in them.

But this, within the budget constraints that we have to live, reires a certain accommodation to looking to the future and trying think about what sorts of facilities will be needed to continue se fields in the future as well as trying to operate them at a el consistent with their investment. It's a difficult compromise a collection of tradeoffs would have to be made, but they're de each year. And I don't think that anybody regards the current level of operation as being appropriate to the investment that's made in the facilities.

Mr. **Fuqua**. You've mentioned in your prepared statement about international collaboration. You said:

> . . . To succeed, it is imperative that the flexibility to negotiate a suitable agreement be maintained. Any premature requirements for specific levels or conditions would likely make it impossible to conclude satisfactory agreements.

What do you mean by the word flexibility and the premature requirements that——

Dr. **Trivelpiece**. Well, from my limited experience in international negotiations, I found that one of the things that's very difficult is that you find yourself with an if-and-only-if instruction from your own home territory. And that is that you can't proceed with doing what you're doing unless you get certain contributions from people overseas.

While well meaning, that type of a statement ties your hands in such a way that it puts into the hands of those with whom you're negotiating the tools by which they can then insist that they get certain concessions and other things that I think is an unhealthy arrangement. And I would hope that such a burden were not placed on whoever it is who is trying to negotiate international agreements in this or any other of these high technology areas. I think that that kind of flexibility to work out the best deal for the United States is an important thing to retain, and the well meaning stiff statement is not all that helpful.

Mr. **Fuqua**. I might add that I agree with you.

Dr. **Trivelpiece**. Thank you. I'm relieved.

Mr. **Fuqua**. In a letter to Dr. Ed Knapp, who is president of Universities Research Association, Dr. Lederman, director of the Fermilab, suggested that the central design group should seriously consider the alternative design to one of the—capability of supporting the colliders at a 40 TeV. (See Appendix 1.)

Can you—have you had a chance to see the letter that——

Dr. **Trivelpiece**. I'm not aware of the letter.

Mr. **Fuqua**. Well, OK. Well, he did suggest maybe a more modified——

Dr. **Trivelpiece**. A different energy level?

Mr. **Fuqua**. No, not a different energy level. Yes, a proton-antiproton——

Dr. **Trivelpiece**. Instead of a proton-proton collider, a proton–antiproton collider.

Mr. **Fuqua**. Right.

Dr. **Trivelpiece**. That's a technical detail which, although I'm familiar with the science to some extent, I think is better addressed to some of the people here who are practicing phycists in this area. But there are quite a few differences regarding this, and you have the experts here to find out the answer to that question.

Mr. **Fuqua**. Thank you. Mr. Barton?

Mr. **Barton**. Thank you, Mr. Chairman. It's always an honor for me to question Dr. Trivelpiece. He and I go back a ways. I used to be the White House fellow to the Department of Energy, and he is the lone eagle from those days. He is still there and doing a tremendous job for the Department of Energy and the United States of America.

I just have a few questions, basically about the cost. In your testimony you estimate a total cost of somewhere between $4 to $6 billion.

How confident are you that this project, if funded as it's currently designed, can actually be built for that amount of money?

Dr. TRIVELPIECE. I think the question of confidence in doing that is in part what we're doing with the process of having a central design group go through and build the prototype magnets and verify in detail the cost-reducing design assumptions to verify that those can be realized in hardware as well as they were realized in the analysis that was made.

I think the position of the Department would be that unless they are assured that it can be done within an agreed upon cost envelope, that we would not recommend for construction.

Mr. BARTON. You've mentioned in your testimony several other projects of a similar nature. I think Isabelle was one. Have there been any other projects that—I realize we've never built a project of this scope, but of similar nature that came in within the original cost estimates? Or is it fair to say that they always escalate, they never deescalate?

Dr. TRIVELPIECE. I don't remember the numbers off the top of my head. I'd be glad to supply them for the record. But there was a GAO study that was done at the request of Congress to look into some of the past activities of the high energy physics program.

My understanding—and I recall it not correctly—but that most of the projects have been brought within cost, and Fermilab, for instance, was brought in under cost. And generally speaking the track record is very good. There is the notable exception with Isabelle, in which case there were quite a few reasons for that. Those reasons have been discussed in testimony before.

Mr. BARTON. You also mentioned the desirability of having industry involved in this project. There was a—one of the magnet designs that was not chosen, that actually I believe came in second place, based quite a bit of its project on industry, private industry participation.

Do you feel that the current design that's been chosen you can get a sufficient amount of industry participation?

Dr. TRIVELPIECE. This project, if it proceeds, will be breaking a certain amount of new ground in terms of how the high energy physics community is going about building facilities which it uses. There has been a tendancy in the past, I think, to build many of the things within the laboratory and to design things on a trial and error basis to get what is needed.

This project is of such a scope and character that I believe it needs to be designed at the outset in such a way that it can be built in its entirety with a complete understanding of the cost. And to me, that means a higher level of industrial involvement in the actual construction of it than has perhaps been traditional in the high energy physics programs in the past.

So, I think it's important to get them involved early on, but at the moment it has still not reached the point where the decision to proceed with the construction is taking place. And the limited funds that are available do need to be used to go through the design activities. It's a compromise, but to the extent that they can, I think they would be well advised to try to incorporate industrial activities or industrial participants in this as soon as possible.

Mr. **Barton**. Mr. Chairman, I don't have anymore questions of Dr. Trivelpiece. I would just like to compliment him. He's been very forthcoming with me in briefing me on this. He's given me a stack of stuff about two feet high, of which I've read about half of it, and I've got a lot of it here with me. It's always a pleasure to have you before our committee.

Dr. **Trivelpiece**. Thank you, Mr. Barton.

Mr. **Fuqua**. Thank you. Mr. Cobey.

Mr. **Cobey**. No questions.

Mr. **Fuqua**. Mr. Stallings.

Mr. **Stallings**. Dr. Trivelpiece, what steps must be taken prior to DOE's endorsement of the construction of the SSC?

Dr. **Trivelpiece**. From this point forward it is to complete some of the technical things that I mentioned earlier, try to put these together into an appropriate case, present that case to the Secretary, and persuade him to incorporate it into an out-year budget. Then subsequent to that, to defend it within the OMB and to have the President endorse it. Subsequent to that it then becomes a matter for you gentlemen here to review and analyze and endorse or modify.

Mr. **Stallings**. Will the DOE publish an on-site specific conceptual design report of the SSC?

Dr. **Trivelpiece**. That I think is the present plan; yes.

Mr. **Stallings**. Do you have any idea when that will take place?

Dr. **Trivelpiece**. A document which can be used to prepare proposals for site selection competition? As I said, it is our present plan not to issue any kind of a request for such proposals until such time as it has been incorporated into a budget and had an opportunity for the Congress to review it, which I cannot see occurring before the spring of 1987.

Mr. **Stallings**. Thank you very much.

Mr. **Fuqua**. Thank you. Mr. Fawell.

Mr. **Fawell**. Thank you, Mr. Chairman. I note in your printed statement you indicate that there was a technical advisory on site criteria, which you shared with the various Governors.

How does that differ from what the final site criteria would be?

Dr. **Trivelpiece**. That was one that was prepared at the Department's request for our use in an RFP, should we ever decide to issue one. It is not the official position of the Department; it is the work of the contractor, the Universities Research Association's agent, the Central Design Group. They prepared that at our request. We have it, we may incorporate some of it, all of it, or none of it into a final document. But at the moment, having sent it to the Governors, the hope was to determine whether or not inadvertently any bias had been incorporated into that that would cause one area to be favored over another. And I have not heard from any of the Governors in regard to that issue.

Mr. **Fawell**. I was thinking that so many of the States are so eager to get going on this, and are at the starting block, and so forth. Do you see that this may precipitate a movement by the

States to assume that this criteria is something they can utilize now to begin to move ahead, stabilize?

Dr. **Trivelpiece.** Well, I did two things. One, I did not include a copy of the report in the letter that I sent to the Governors. And in that letter to the Governors are some very clear caveats about what the circumstances are. And I couldn't recite them from memory at the moment, but they are, in effect, caveat emptor with regard to the States making any motion with regard to this at the moment. The Department is not encouraging anyone to take any steps. They are spontaneous, and I think their mutual stimulation is involved in them.

Mr. **Fawell.** Well, I am new to the Congress, so this question may not be really appropriate. But I seem to detect a cooling of the ardor of DOE for the super collider. I note just such wording that, as you stated, I'm not proceeding in a path which assumes we won't do this. When you look at the time schedule here, it would appear that at the earliest there wouldn't be any site selection until sometime in 1989.

It seems to me, as a newcomer, that from what I had heard when I first became acquainted with this subject that it was something that people felt was going to take place. Now there seems to be a great deal of doubt as to whether that is so. If there is a cooling of the ardor, why?

Dr. **Trivelpiece.** No; I don't think there is. I think that in fact the Department has tried to maintain a very stable and evenhanded approach to this, and requesting funds to get the necessary information available. And if we were not interested in proceeding, we probably would not have asked for the funds. That would have been the simplest way by which that could have been taken care of.

The object is to gather the information that is needed, and then to try to come to some rational decision and make the appropriate recommendation. The thing that changes, I think, is the outside Department waxing and waning of enthusiasm by individuals who would like to build and operate this, and industrial organizations that would like to participate in the construction, and the various States and organizations that would like to compete for it.

But our approach, as best we can do it, has been to be about as even and level as we can in terms of not trying to give any signal that we have suddenly increased our interest in it nor that we have decreased interest in it.

Mr. **Fawell.** Thank you.

Mr. **Walgren** [acting chairman]. Thank you, Mr. Fawell. Let me ask, Dr. Trivelpiece, you indicate in your testimony something to the effect that we couldn't really deal with the international cooperation question until our own plans were clear. I think that's the wording that you used in your testimony.

Isn't that kind of a chicken and egg thing? How do we decide whether or not we're going to deal internationally until we make a decision, and yet we're not firm, are we, on our own decision of whether that's going to be done as a total American project?

Dr. **Trivelpiece.** Well, I've made several trips to Japan and Europe to discuss with various people various aspects of this project—some of whom are here today in the room who will be witnesses. In doing that, we are talking with them on a hypothetical basis, on a "what if we were to do this," and so what is it that you would be interested in doing. And in that regard, we have invited scientists from both the European Continent and from Japan to participate in the SSC planning process to the extent that they wish to on the grounds that if we get to the stage of proceeding, then the more knowledge they have, the more informed kind of a decision that they would be in a position to make at that particular time.

However, it is not possible to say to anybody at the moment that in exchange for this, we will commit to the following, because we have nothing to commit to. So it was in that spirit that that particular remark was included in my prepared statement. It's just that we don't have anything concrete to offer, therefore we can't expect anything concrete in return.

Mr. **Walgren**. Has the trend toward wanting to keep everything within the American community only on a scientific basis raised its prospect in this area as well?

Dr. **Trivelpiece**. No. I think there is general recognition that a project of this sort is almost certainly going to be an international activity one way or another. And that the idea or the luxury that this would be done entirely within the United States exclusively by U.S. scientists with exclusive U.S. support is unrealistic. And I don't see any particular problem with that. I think that when the time comes, that appropriate participation will take place.

And as you perhaps know, there is a substantial investment on the part of the United States in some of the European activities as there is a substantial investment on their part in some of our activities here. Practically no paper ever published in this field is published by individuals from a single country now. It's quite an international activity to begin with, and I would expect that to continue.

Mr. **Walgren**. Thank you very much on behalf of the committee. We have a vote that the members are responding to. Mr. Fuqua will be back directly, as will the others following him. And at this point we should recess for only several minutes, I would think maybe 5 minutes, before he would be expected back. And we would begin with the first panel at that point.

Thank you, Dr. Trivelpiece.

Dr. **Trivelpiece**. Thank you, Mr. Walgren.

[Trivelpiece questions and answers for the record follow:]

POST-HEARING QUESTIONS AND ANSWERS

Relating to the

OCTOBER 29, 1985 HEARING

Before the

SUBCOMMITTEE ON ENERGY DEVELOPMENT AND APPLICATIONS
COMMITTEE ON SCIENCE AND TECHNOLOGY
U.S. HOUSE OF REPRESENTATIVES

WITNESS: DR. ALVIN W. TRIVELPIECE
DIRECTOR, OFFICE OF ENERGY RESEARCH

Question 1: - You stated on page 8 of your testimony that you notified all the governors that the site criteria document was available. What response have you received to date?

Answer: The letter to the governors suggested they contact the Central Design Group for the siting parameters document, and to date the Central Design Group has received 347 requests, from governors and others in 39 states interested in the SSC. At the Department, we have received various inquiries about the SSC from 28 states.

Question 2: - What steps has the Department of Energy, in particular, and the U.S. high energy physics community, in general, taken to discuss with CERN possible U.S. participation in the construction and operation of the Large Hadron Collider?

Answer: Most U.S. high energy physicists believe that the energies of a Large Hadron Collider (LHC) in the Large Electron-Positron (LEP) tunnel are not sufficient for the required exploration of the TeV mass region. In addition, there is the major problem that trying to operate two of the orld's frontier machines (LHC and LEP) in the same tunnel would cause onsiderable interference, delays, and frustration on all sides. Among ther things, this would adversely impact the considerable U.S. work that as gone into preparation for LEP experiments. As you are aware from rofessor Rubbia's testimony today, there are no European plans as yet to uild an LHC; and his committee is not charged to make its recommendations ntil mid 1987. For these and other reasons, the Department has not iscussed with CERN possible U.S. participation in the construction and peration of an LHC.

With regard to the U.S. high energy physics community, I am not aware f any organized activity and I am not in a position to comment on actions hich may have been taken by individual physicists.

Question 3: - The Central Design Center has been distributing a newsletter which Committee Members and staff have found informative and helpful in keeping up-to-date with the SSC program. It is claimed that DOE Headquarters recently ordered the Central Design Group to stop distributing this newsletter. If so, why? What will take its place?

Answer: The Department did request that the Central Design Group stop distributing the newsletter in its previous format. Distribution of an informational report with a different format is being initiated.

Question 4: - What, if any, classified research will be done using the Superconducting Super Collider? Specifically, will any research be done pertaining to the Strategic Defense Initiative?

Answer: At present there are no plans for classified research using the SSC. In the past, the development and operation of accelerators for high energy physics has benefited the Nation's security primarily through the new technology, expertise, and training associated with these accelerators, their development and use.

Question 5: - You mentioned that it is likely that the $6 billion cost of the SSC will come down by next spring. What is your estimate of the total cost?

Answer: The SSC R&D program has been highly successful and there are clearly improvements (e.g. superconducting wire) which will result in a reduction of SSC costs; however, it would be premature for me to speculate on the results of the detailed cost estimates that will be done this winter as part of the Conceptual Design Report. The Department does not plan to present any new cost projections until we have had the opportunity to review this report next spring. However, I do not expect a radical change from the cost estimates made for the Reference Designs Study.

Question 6: - Given our budget deficit and the likely passage of a deficit-reduction bill—at what cost does the SSC become unjustifiable? More specifically, at what cost will the Department of Energy withdraw its support of the project?

Answer: These are issues which will be intensively discussed within the Department during the coming year. While this is obviously not the best of imes to be discussing new projects of any sort, I believe that as a Nation e must strive to maintain our excellence in basic research. Our economic ell-being and national security depend on it, and the responsibility for ich support clearly rests with the Federal Government. High energy ysics, with its studies of the most fundamental aspects of matter and ergy, forms one of the bases of understanding for some other fields of ience and technology. It is clear that careful planning will be required order to maintain our most important basic research objectives in these essful times.

Question 7: - The Committee on Science and Technology and the Department of Energy have repeatedly stated their intent to involve industry very closely in the design and production of the SSC. Yet it appears that the national labs have designed the SSC magnet with little direct input from industry. Furthermore, the national laboratories plan to build the first several magnets themselves. Obviously, we all wish to avoid repeating the mistakes of Isabelle. However, it appears that the stated intentions and desires of this Committee and your Department have not been followed.

Question 7a. Wouldn't it have been better to involve industry much more closely in the design process of the high-field magnet?

Answer: There has been considerable industrial input and participation in the work on the high-field magnet. Industrial firms have developed manufacturing plans and plant layouts for magnet production and have made detailed cost estimates for the magnets. The close collaboration between U.S. industry, the national laboratories, and university researchers to improve the quality of superconducting wire produced in this country has been highly successful and has greatly aided the high-field design. There have been numerous other areas of industrial participation, including cryostat design and applications of "multiwire" technology to superconducting correction coils within the bending magnets.

Now that we are focused on one magnet design type, we intend to involve industry more closely, so as to further the cost and performance optimization through commercial processing.

Question 7b: If industry is expected to build the magnets for the SSC, why are the national labs building the first string?

Answer: The magnets for the initial half-cell string test are prototype magnets, still in the R&D stage. Up to now, close interaction with the accelerator theorists and systems engineers has been required to determine possible trade-offs on specifications. Current plans now call for industrial firms to send personnel to observe and work with laboratory personnel on these magnets. The Department expects that this will lead to strong ndustrial participation in prototype magnet production as R&D proceeds eyond the initial half-cell test.

uestion 7c: - Design and production costs are consistently higher at the ational labs than in industry. What do you think of the proposal of ending out the SSC to industry for competitive bids?

nswer: The expertise and production capabilities of industry are expected o be used in the fabrication of the SSC magnets, cryogenics and other omponents, and in the conventional construction for the facility, should e Department decide to proceed with the project. Accelerators for high ergy physics are one-of-a-kind, state-of-the-art machines with the R&D, sign, construction, and operation closely directed by the physicists volved. However, fabrication of components and subsystems has always lied primarily on industry. This approach has worked well in the past h the high energy physics program having an excellent record for pleting large high technology facilities close to budget and on schedule.

Question 7d: - Please comment on the level of industry involvement in the research and development of the low-field design. How important was the level of industry involvement in the final selection criteria?

Answer: General Dynamics (GD) was given a kit of parts by the Texas Accelerator Center and asked to assemble low-field magnets. For this, GD developed cooling and assembly methods, in some cases after some trial and error, as might normally be expected. As Dr. J. K. Hulm testified, the Magnet Selection Advisory Panel solicited and took into account comments from three industrial consultants (from Westinghouse, Brown Boveri, and General Dynamics) on factors relating to all aspects of industrial production of the SSC magnets. They concluded that either style of magnet design can be produced in industry and pointed out that magnet models of both designs have been assembled in industry (two of the superferric style at General Dynamics and eight of the cosine theta style at Brown Boveri).

**estion 8: - Fermilab and Brookhaven both have in-house "magnet
ctories". How many people are employed by each laboratory in these
ants and what is the total budget, including overhead, to support them?
e these factories in competition with American Industry?**

**swer: Fermilab and Brookhaven have in-house superconducting magnet
brication capabilities as integral parts of the Technical Support Division
Fermilab, and the accelerator R&D effort at Brookhaven. Superconducting
gnet technology is a new emerging technology. The entire Tevatron super-
nducting magnet ring was in effect an R&D demonstration of the feasibility
superconducting accelerators. In the case of the Tevatron, Fermilab
ocured magnet components ranging from superconducting wire, vacuum bore
pes, iron laminations and cryostats from industry. The winding of the
perconducting coils and the assembly of the magnets were done in-house
re the expertise of the Fermilab physicists and engineers could be most
ectively applied to the effort. Frequent design changes and evolution
k place during the course of fabricating the 1000 magnets now in the
atron. This type of evolving technology is not well suited to industrial
duction. The capabilities at BNL have never been used to mass produce
nets but have only been used for R&D purposes to test new ideas and to
elop prototypes. If we decide to proceed with construction of SSC and
er a large scale magnet fabrication effort, we anticipate that industry
fabricate the magnets.**

PANEL 1: STATUS AND PLANS FOR CERN

Mr. **Fuqua**. Our first panel of witnesses, Prof. Herwig Schop
and Prof. Carlo Rubbia will discuss the status and plans for CE
the European Laboratory for Elementary Particle Physics
Geneva, Switzerland. Professor Schopper is beginning his sec
term as director general of CERN. Dr. Rubbia is professor of pl
ics at Harvard University, is chairman of the Working Group
the Scientific and Technological Future of CERN, and shared
Nobel Prize in Physics in 1984 with his CERN colleague, Si
van der Meer.

If you two gentlemen will switch your name—oh, that's all ri
Professor Schopper, we'd be pleased to hear from you at this t

STATEMENT OF DR. HERWIG SCHOPPER, DIRECTOR-GENER
CERN, GENEVA, SWITZERLAND

Dr. **Schopper**. Mr. Chairman, it's a great honor and pleasur
me to testify here on the current and future program for CER
particular since there is a longstanding tradition of an exce
collaboration between the United States and Europe, and speci
ly with CERN.

Now, CERN is the European Laboratory for Elementary Pa
Physics. Indeed, it is the oldest European organization, older
the Common Market, and is now supported by 14 member st
Portugal joined this year. The scientific program is mainly ca
out by scientists from universities and national laboratories i
member states, but the participation of physicists from nonme
states for many years played a very important role.

In total, there are about 3,000 outside users, of which abou
come from nonmember states, and more than 200 scientists
the United States are working at CERN, many others fro
Soviet Union, Japan, China, Canada, Israel, and many other
tries. So, as far as the scientific program is concerned, CERN
way has become a world laboratory.

All experiments are planned, carried out, and even financ
international collaborations who, however, do not contribute t
operation of the machines and the facilities.

As far as the current scientific program is concerned, I th
shall be very short because more information is given in my
ten version. Let me just mention that our main research faci
still the so-called SPS, a proton accelerator with a max
energy of 450 GeV, which is now also possible to collide p
against antiprotons. And until very recently, these were the
est energies available in a laboratory. And the big success
machine, both from the technical point of view and from the
ics point of view, has brought two Nobel Prizes for Mr. va
Meer and Mr. Carlo Rubbia.

Now, a few weeks ago these energies were surpassed by the
tron at Fermilab, which is now the largest proton accelerat
also the largest proton-antiproton collider in the world, with
gies about 2½ times bigger than the SPS. This is also th
large superconducting accelerator that has been operate
therefore I should like to use this occasion to congratula
Fermi Laboratory for this marvelous success.

Now, in spite of the higher energies now available at the Tevatron, CERN will continue this program in the coming years, but certainly at a somewhat reduced level, and will have to concentrate on some special questions. But here, as I said, I want to stop as far as the current program is concerned and would leave the rest to the written statement.

Now, the major activity of the laboratory nowadays is the construction of the so-called LEP accelerator, LEP colliding ring, which was approved at the end of 1981 and whose first stage is to be planned to be finished by the end of 1988. What is unique in this project is that it has to be constructed within a constant budget, and with no additional staff. And the project costs approximately 1,000 million Swiss francs, something like $460 million, but not including personnel and the contingencies, and no experiments.

I'm glad to say that so far we are not only within the schedule, but also within the budget within a matter of a few percent. And with respect to a question which came up more recently here, I think high energy physics in general has a tradition to stay well within budget and schedules, and that's not by chance. I think the reason is that it is the tradition of high energy physics laboratories to plan very carefully their accelerators. They take the technical responsibility to build prototypes, to find technical solutions, and they keep the responsibility in realizing and carrying out the project. And because of that, I think the tradition is, as I said, that usually all projects, or most projects, are carried out within schedule and foreseen budgets.

Now, LEP was originally designed and optimized, and its size determined by a design energy of 100 GeV per beam. And the idea was to build the largest electron accelerator which seemed to be feasible at the present time. The physics of electrons turning on a circular orbit has the consequence that the circumference has to be rather large, and for this optimization of 100 GeV, it gave a circumference of 27 kilometers, which is the largest accelerator which is presently under construction.

Because of financial limitations, I mentioned that we have to stay within a constant budget, and also because there's the Z° particle discovered by Professor Rubbia—LEP will start operation at lower energy, and the initial energy foreseen is about between 50 and 60 GeV per beam. However, LEP is conceived in such a way that by simply adding superconducting cavities in places in straight sections which were left free, one can eventually upgrade the energy to its final design energy of about 100 GeV.

The big question, of course, is when that will be done. Well, the most important argument should be physics. We'll have to see what the physics needs after the startup of LEP will be. And of course there are also the available funds that will determine the rate at which this upgrading can be done, and certainly it will extend into the early years of the coming decade.

I want to mention also that four large experimental facilities for use at LEP have been approved and they are under construction. About 1,100 physicists are involved in these four international collaborations. The interesting thing is that they contribute to the financing of these detectors, the total cost of which is about 320 million Swiss francs, or about $150 million. And indeed CERN itself is only providing a quarter of this total sum.

So, here's an interesting example of an international collaboration of financing these large projects.

To keep control and monitor the progress of the construction of these detectors, and in particular also the financing, we have established special management structures like finance committees for these various experiments and so on.

Now, let me come to the future options at CERN. It lies in the nature of a circular electron accelerator that a relatively large fraction of the cost has to be spent for the construction of the tunnel. For this reason, the use of the LEP tunnel for future options had already been envisaged at the time of the approval of LEP, and I pressed very hard at that time that the circumference of the tunnel and also its cross section should be made as large as compatible with geological, financial, and other constraints. In particular also, we made sure that the LEP magnetic ring itself inside the tunnel will be installed in such a way as to leave enough room for a second magnetic ring on top of it.

There is wide, if not unanimous, agreement that as the next step for the exploration of the microcosmos, a large hadron collider in the multi-TeV range should be built. Although I also should like to add that maybe there is not complete unanimity as far as the energy of such a collider is concerned because that depends a little bit from the starting conditions for such a project.

As I mentioned, such a collider ring—a superconducting collider ring could be installed in the LEP tunnel, and one could also envisage both the collisions between protons and protons or protons against antiprotons, which means two or one ring—which is a question that was raised a few minutes before, is a question, I think, which needs further study.

Now, in our case, the existing radius of the existing tunnel determines the radius of the machine, and therefore the maximum achievable energies are determined by the magnetic field of the bending magnets. Therefore, we are interested in the development of magnets with very high fields, and we think that magnets with about 10 Tesla should be in reach. But this will require some development. And with such magnets we could produce about nine TeV beams, nine TeV per beam in the LEP tunnel.

If one would be satisfied with present day techniques, which means about six or seven Tesla per beam, one could get up to six TeV per beam.

Now, CERN, of course, is fully committed by the present program well until the beginning of the next decade. Nevertheless, discussions on further options and further possibilities after LEP I and the upgrading of LEP started already some time ago in view of the very long lead times, both for the technological developments, the preparation of a project and its authorization.

ECFA, the European Committee for Future Accelerators, held a workshop on a large hadron collider in the LEP tunnel already in March of 1984, and a collaboration between laboratories and industry interested in the development of high field magnets is considered. In fact, we decided last week to make a proposal to the European research ministers to support such a development inside the Eureka Program.

Then a group of experts, a committee for the long range future of CERN, has been set up under the chairmanship of Professor Rubbia. And this committee is studying various variants of a hadron collider in the LEP tunnel, and Dr. Rubbia will give more details on what they are considering. The report of this committee is expected in the summer of 1987.

I think it's very unlikely that our member states will make a decision before more information is available on various items—first of all on physics. I think one would like to wait for what comes out from the present operation of our SPS, but also of the new energy range now available at the Tevatron. One will want to wait for new technical possibilities, and in particular what kind of magnetic fields one will be able to obtain. It will also be very interesting to watch the operation of SLC at SLAC. And last, but not least, one will wait for the outcome of the report of Professor Rubbia's committee.

On top of this, a political decision will have to be taken: what the CERN budget level should be at the end of the LEP construction period, because during the construction of LEP it was agreed that the budget level would be kept constant. And we have started now discussions of what the budget level should be after 1989. I don't think there's a chance that the overall budget, supported by the 14 member states, will go up.

However, the situation could change drastically if it were possible to find supplementary funding, maybe outside the normal CERN budget, for the construction of a hadron collider. And such support could come either from Europe, from some of the member states, or, of course, by international collaboration, and this possibility is being pursued.

Allow me to close with a few general remarks. To explore the rich and promising field of subnuclear matter, different kinds of tools are needed. I think we need more than just one world accelerator. However, since these facilities become more complex and costly, a further concentration in number and location of laboratories probably will become unavoidable. But I think we should have a program of complementary facilities to be able to approach the questions from different points of views.

I believe, therefore, that it's very important that more than one continent—or as nowadays it's sometimes called regions—should support this field of high energy physics or subnuclear physics.

For the present generation of large accelerators, such a complementarity and cost effectiveness has already been established. The United States has built the largest proton accelerator, the Tevatron, which can be used for both so-called fixed-target physics and hadron collisions; whereas in Europe we are building the largest electron-positron collider.

I believe that such a complementarity should also be aimed at for the next generation of accelerators after the Tevatron and LEP. The question was raised just a few minutes ago how such a complementary program could be achieved, what kind of mechanism one could use. I would like to mention here one possibility, which is the high energy physics panel—in fact chaired by Dr. Trivelpiece—of the Economic Summit Working Group. And there this problem has been discussed during the last few years. At the moment it was not possible yet to propose a coherent, complementary scenario, but maybe in the not too distant future one might arrive at such a possibility.

If one can achieve such a complementary program, the uniqueness of these facilities will demand that international, intercontinental cooperation should be even more intensified. One can note with great satisfaction that it has become already now a tradition in high energy physics that physicists from one continent participate in an essential way in experiments in the other continents, including major contributions to the funding. Thus, United States groups play a leading role in some of our LEP experiments, whereas European groups participate in an essential way in Tevatron experiments. And there are many other example of mutual benefits.

It would be interesting to explore the possibility of extending this practice of funding in the other continent to the construction of accelerators. Now there is already a full exchange of all available information between laboratories and groups, and in particular also concerning the studies for the SSC. And it's sometimes very strange to see that in spite of a strong element of competition, which certainly provides a strong driving force, there is this mutual give and take which even means helping each other by exchanging people, exchanging whole pieces of equipment.

I believe in our field duplication is, therefore, largely avoided and cost effectiveness achieved. As a result, I think that high energy physics is a field where the effectiveness in terms of scientific output relative to the resources is extremely favorable. Therefore, I trust that this exciting field, which is full of promises, which is an essential part of human culture and has important technological and educational consequences will be further supported, and I hope vigorously supported, on both sides of the Atlantic.

Thank you, Mr. Chairman.

[The prepared statement of Dr. Schopper follows:]

25 October, 1985

THE CERN HIGH ENERGY PHYSICS PROGRAMME

Herwig Schopper, Director-General

CERN - Geneva (Switzerland)

Statement to the Subcommittee on Energy Development and Applications
of the US House of Representatives, Washington, D.C.
29 October, 1985

CERN is the European Laboratory for Elementary Particle Physics supported by fourteen Member States. The scientific programme is mainly carried out by scientists from universities and national laboratories in the Member States, but the participation of physicists from non-Member States is welcome. In total about 3000 outside users of which about 600 come from non-Member States (e.g. USA, USSR, Japan, China, Canada, Israel), participate in the various CERN programmes. All experiments are planned, carried out and financed by international collaborations.

THE CURRENT SCIENTIFIC PROGRAMME

The main research facility is at present the SPS, a proton accelerator with a maximum energy of 450 GeV. It was originally conceived and operated as a fixed-target accelerator. The development of an antiproton source using the invention of beam cooling made it possible to convert the SPS several years ago into a proton-antiproton collider facility providing centre of mass energies of 630 GeV. For an exploratory run this energy was pushed to 900 GeV in a pulsed mode. Until recently these were the highest energies available in a laboratory and made possible the discovery of the W and Z particles.

A few weeks ago these energies were surpassed by the Tevatron at Fermilab where the first large superconducting accelerator is being operated with great success. There it was demonstrated that centre of mass energies of 1600 GeV are feasible. In spite of the higher energies available at the Tevatron the CERN SPS programme, both for fixed-target and collider physics, will continue, although at a reduced level, in the coming years and very likely even beyond the end of this decade. In order to be able to carry out attractive and competitive experiments an improvement programme is now under way. It includes the construction of a new antiproton accumulator ACOL (to increase the antiproton intensities by more than a factor of 10) and the upgrading of the two major collider experiments. The fixed-target SPS programme is increasingly attracting more physicists who want to use the relativistic particles (including light ions) to explore the nuclear structure, including many from US National Laboratories.

The powerful antiproton source is also used to produce very high quality beams of very low energy antiprotons with the storage ring LEAR. A community of about 250 physicists (including a sizeable participation of US scientists) is exploiting this unique facility not only for the study of problems of elementary particle physics, but also for atomic spectroscopy and nuclear physics.

THE LEP PROGRAMME

The major part of the activities of the Laboratory is devoted to the construction of the LEP accelerator which was approved at the end of 1981 and whose first stage will be finished by the end of 1988. It has to be realized within a constant budget, i.e. without supplementary funds or personnel. The project costs approximately 1000 million SF (460 million US $) not including personnel and contingencies.

LEP is an electron-positron collider with a design energy of 100 GeV per beam yielding centre of mass energies in the range of 200 GeV. The optimization of LEP aiming at the highest presently feasible electron energies means that the ring has a circumference of about 27 km, so it is the largest accelerator now under construction.

Since electrons and positrons are point-like particles their full energy is available for the fundamental interactions and the observed events are clean and easy to interpret. Because of the complicated structure of the proton only about 1/6 of the nominal proton energy is useful on the average for the fundamental interactions and, in addition, the events are more difficult to interpret. On the other hand, electrons are more difficult to accelerate in circular machines because of synchrotron radiation losses, and hence electron machines are larger in diameter than corresponding proton machines.

Because of financial limitations LEP will start operation at an initial energy of (or somewhat above) 50 GeV per beam which subsequently will be increased in steps by adding superconducting accelerating cavities in free straight sections. A vigorous programme for the development of appropriate superconducting cavities is being pursued at CERN in collaboration with other laboratories and with industry. The time scale for the upgrade of LEP to its design energy of 100 GeV per beam will be determined by physics needs and by the available funds.

Four experimental facilities for use at LEP have been approved and they are presently under construction. 1100 physicists are involved in these four international collaborations contributing to the total cost of the detectors of about 320 million SF (150 million US $) mainly in kind by providing components. These facilities are expected to be operational at the beginning of 1989 at the turn-on of LEP.

FUTURE OPTIONS

It lies in the nature of a circular electron accelerator that a relatively large fraction of the cost has to be spent for the construction of the tunnel. For this reason the use of the LEP tunnel for future options had been already envisaged at the time of its approval. The circumference of the tunnel and its cross section were made as large as compatible with geological and other constraints. In particular, the LEP magnet ring will be installed in such a way as to leave room for a second ring of magnets on top of it.

There is wide agreement that as a next step for the exploration of the microcosmos a hadron collider in the multi- TeV range should be built. As mentioned above such a collider using superconducting magnets could be installed in the same tunnel on top of the LEP magnet ring. One could envisage both either collisions between protons and protons or protons and antiprotons. Since the radius is given by the existing tunnel the achievable energies are determined by the magnetic field of the bending dipoles. With 10 Tesla superconducting magnets energies of about 9 TeV per beam could be obtained in the LEP tunnel. However, such magnets require considerable technological development. With present-day techniques one could achieve an energy about 6 TeV per beam.

Although CERN is fully committed by the present programme until the beginning of the next decade, discussions on further options already started some time ago in view of the long lead times both for the technological developments and the authorization procedures. ECFA (European Committee for Future Accelerators) held a Workshop on a "Large Hadron Collider in the LEP Tunnel" in March 1984 and a collaboration between laboratories and industry interested in the development of high field magnets is under consideration. A group of experts is at present studying various variants of a hadron collider in the LEP tunnel and also other options. Their report is expected in the Summer of 1987.

It is very unlikely that a major decision will be taken by the CERN Council before more information is available on the physics needs (results from SPS and Tevatron), on new technical possibilities (development of superconducting magnets, operation of SLC) and before the report of the experts committee has been discussed. In addition, a political decision on the CERN budget level after the LEP construction period (i.e. after 1989) will have to be taken.

GENERAL REMARKS

To explore the rich and promising field of subnuclear matter different kinds of tools are needed. Since these facilities become more complex and costly a further concentration in number and in location will become unavoidable, but a certain number of complementary accelerators will be required to approach the open questions from different directions. Hence it seems necessary that more than one region (continent) continues to work effectively in the field of high energy physics.

For the present generation of large accelerators complementarity and cost effectiveness have been established. The United States has built the largest proton accelerator, the Tevatron, which can be used both for fixed-target physics and hadron collisions, whereas Europe is building the largest electron-positron collider, LEP. Such a complementarity should also be aimed at for the generation of accelerators after the Tevatron and LEP. The uniqueness of these facilities will, however, demand that intercontinental cooperation be intensified. One can note with great satisfaction that it has become already a tradition in high energy physics that physicists from one continent participate in an essential way in experiments in other continents, including major contributions to the funding. Thus, US groups play a leading role in some of the LEP experiments, whereas European groups participate in an essential way in Tevatron experiments. It would be interesting to explore the possibilities of extending this practice to the construction of accelerators.

But even now there is a full exchange of all available information between laboratories and groups and in spite of a strong element of competition providing a strong driving force, they even help each other in many practical ways by exchange of people and instruments. Thus, duplication is largely avoided and cost effectiveness achieved. As a result high energy physics is a field where the effectiveness in terms of scientific output relative to the resources is extremely favourable. In addition, it provides a strong incentive for technological developments by industry.

Mr. **Fuqua.** Thank you very much, Dr. Schopper.

Dr. Rubbia, we're delighted to have you back again. I think the last time you were here you had to leave to go teach a class.

Dr. **Rubbia.** That's right.

Mr. **Fuqua.** I hope maybe you're excused this afternoon.

Dr. **Rubbia.** Should I read my testimony?

Mr. **Fuqua.** Please, go ahead.

STATEMENT OF DR. CARLO RUBBIA, CHAIRMAN, WORKING GROUP ON THE SCIENTIFIC AND TECHNOLOGICAL FUTURE OF CERN, GENEVA, SWITZERLAND; AND PROFESSOR, DEPARTMENT OF PHYSICS, HARVARD UNIVERSITY, CAMBRIDGE, MA

Dr. **Rubbia.** Mr. Chairman, members of the committee, I would like to summarize briefly my views on the future options of colliding beam accelerators.

Colliding beams are of interest since they improve the effectiveness of impacts between relativistic particles. New particle states with high masses can then be produced. Historically, the first colliding beams were made for electrons and positrons. The development of hadron-hadron; namely, proton-proton and proton-antiproton colliders has proceeded much more slowly mainly because of the high energies at which colliding beams become effective, and for more other very subtle technical reasons which I will not discuss.

The first proton-proton collisions were observed in 1971 at the CERN-Intersecting Storage Rings, the ISR. The first proton-antiproton collisions, somehow the equivalent of the electron-positron collisions, were observed again at CERN in 1981 at the SPS collider. It is a few weeks ago that the great news of the successful operation of the TeV I proton-antiproton collider at Fermilab has broken out, extending to the USA the field in which CERN had made its own for almost 15 years.

Energy of collisions has also grown considerably with time. It was 62 GeV in the center of mass for the ISR, it has reached 900 GeV at the SPS collider, and it's now 1,600 GeV at Fermilab. In comparison, the largest electron-positron machine under construction; namely, LEP-2, will barely achieve 200 GeV. However, quarks rather than protons are relevant in hadron collisions, and therefore only one-fifth or one-tenth of the energy of the collision is useful.

In spite of the large nominal differences, LEP-2 and TeV I are complementary machines, and they will explore comparable energy scales. It is such a complementarity between the European and the U.S. programs that is of great importance in our field, as pointed out by the previous speaker.

The third possibility; namely, collisions between electrons and protons, is under construction in Germany with a revolutionary machine called HERA, in which 800 GeV protons collide with 30 GeV electrons. The realization of this machine has been made possible by an unprecedented scheme of international collaborative efforts. Although DESY is and remains a German laboratory, Italy is providing for 50 percent of the superconducting magnets. France is making the focussing quadrupoles, Canada is building the accelerating system, Holland is building the controls, et cetera. Money and know-how are extensively pooled in order to build such a very large and complicated set of accelerators. In my view, this is a model for the future, and it must be observed with great interest as an example for future enterprises.

New initiatives are widely discussed in order to reach even higher energies, and in the expectation that also beyond LEP-2 and TeV I some new phenomena are likely to occur. It should be stressed, however, that there is no exact prediction if, and at which energy, new phenomena to complete the picture of matter and of forces will be found.

Most fundamental and long-awaited discoveries—like, for instance, the so-called Higgs particle—may even come out from already existing machines with hadrons or near-future electron colliders. The high-risk nature of each individual high energy physics initiative is self evident. Nevertheless, we have no other way of finding it out except the traditional method of following the path of ever-increasing accelerator energies.

Production of new particles of higher masses and their related phenomena are inevitably associated with smaller observational probabilities. This is a very familiar effect. Going from atomic to nuclear, and from nuclear to constituents physics, we have experienced an enormous overall drop in the rate of occurrence of the phenomena. Heavier members of the particles families need not only higher energies, but also a large number of collisions in order to be observed.

For instance, at the CERN collider, the Z° particles occur at the rate of one every billion interactions. In the case of a hypothetical Z-like particle of 3 TeV, produced, say, by a 15 TeV collider, the fraction of good events will drop to about one good event in a trillion of all events. If as many as 10 million of very complicated collisions are processed every second, the good event rate will not exceed one event a day.

Our discovery of the W and Z particles were particularly easy because of their unique and spectacular signature, and because we knew where and what to look for. This is no longer so for the next steps, for which neither the energy nor the signature are precisely known. Many of the signatures which we want to search in the new energy domain—like, for instance, the Higgs or supersymmetric particles—are rather elusive and an immense amount of data processing is necessary in order to identify processes occurring at a level from 1 every 10 billions to few trillions of all events.

There is a significant chance that important phenomena may become masked by the huge number of ordinary collisions, and that the unexpected physics may be missed.

A 40 TeV collider, with as many as 10 million events per second, will have an impact in the new physics somehow equivalent to the one of the CERN collider with the 1,000 events per second, which is much too small to be of practical interest in very rare high energy phenomena. To the extent that we believe for a present collider it has an adequate luminosity, by the time we achieve 40 TeV, we must be able to handle in excess of half a billion interactions every second. Clearly we need radically new types of detectors as well.

Electron-positron colliders of energies much larger than what is possible with LEP, and which are necessarily linear colliders, are not effected by detector limitations since the total event rate is very low and almost every event is good. Event identification poses, therefore, relatively little or no problem. Although, in principal, quark-quark and electron-positron collisions have similar couplings, and therefore the same new processes should occur in both cases, the absence of the huge total event rate makes electron-positron colliders very attractive and detector construction easier.

Unfortunately, we are not quite ready to construct such machines, which still need detailed design studies and the experimental confirmation of several fundamental assumptions; most of which will be probably provided by the SLAC linear collider. Its first operation in less than 2 years will no doubt be a significant milestone in our field.

In this field, our research and development is in itself a very interesting feature because of the new technology intakes. Thus, we face the dilemma; should the next European initiative be a proton or an electron collider? Studies on both alternatives are actively pursued.

It is believed, however, that a phase of hadron collisions in the LEP tunnel, as mentioned by Dr. Schopper, would give an excellent chance of not losing the interest in the discoveries of high energy physics and of making a smooth and gradual progress in the field. This phase should not appear as an attempt to compete with the ultimate world collider at highest energies and luminosities either with electrons or with protons. These views are strongly supported by the European community of physicists, and I believe, many of the U.S. users at CERN.

The rapid realization of the LHC is today primarily a matter of money. If resources were to be available, one could construct it and operate it with a few years of delay from the beginning of LEP. Now, the real question is how much money? I shall give an approximate money estimate.

Assume a single hadron ring added to the electron ring along the 27 kilometers of electron machine under construction. This ring is one-third of the SSC in length, and with only one-half of the magnets in it—and this is a proton-antiproton alternative. Roughly this is a factor of six reduction over the SSC accelerator components, presently estimated to about $1 billion. Estimates based on the HERA magnet costs from industry, and assuming a factor of 2 reduction from these unit prices because of the huge quantity, gives approximately twice this estimate, namely $250 million. Therefore a proton-antiproton machine of one-third of the SSC energy and one-tenth of the rate of event can be built for under $300 million.

The LEP tunnel, with an additional hadron ring and a field of 8 Tesla, is capable of storing particles at about 7,500 GeV, and will permit a broad spectrum of interesting and complementary investigations. It will permit electron-positron collisions up to 200 GeV. It will permit proton-antiproton collisions with 15,000 GeV in the center of mass, an event rate in the vicinity of 10 million events per second, and will provide an electron-proton option at 10 times the energy of the present constructed HERA.

I believe that it is only natural that, at CERN, scientists wish to continue to work in the field of hadron colliders, in which they have been actively working for so many years. However, it should be pointed out that the hadron collider in the LEP tunnel is not an alternative to the SSC, because it's half, far less ambitious goals, offers one-third of the energy and one-tenth of the interaction data. It is, however, an intermediate step which we believe is worth considering and exploiting, perhaps, in the way toward the largest energies.

Thank you.

[The prepared statement of Dr. Rubbia follows:]

STATEMENT BY CARLO RUBBIA TO THE SUBCOMMITTEE ON
ENERGY DEVELOPMENT AND APPLICATIONS OF THE
U.S. HOUSE OF REPRESENTATIVES, WASHINGTON, DC

October 29, 1985

Mr. Chairman and Gentlemen:

I would like to summarize briefly my views on the future options for colliding beam particle accelerators.

Colliding beams are of interest since they improve the effectiveness of impacts between relativistic particles. New particle states with high masses can then be produced. As an example, I would like to recall that in order to create a W or a Z particle (which are the heaviest elementary objects so far produced by man) we have to concentrate the amount of energy equivalent to the rest mass of a pair of iron and anti-iron nuclei, namely 100 GeV, in a volume which is one billion times smaller than the size of such a nucleus.

Historically, the first colliding beams were made for electrons and positrons. Although the first experimental electron-electron collider was operated at Stanford University, the development of the modern electron-positron colliders has taken place mostly outside the U.S.: the first machine was developed in Frascati, Italy, followed by colliders in the Soviet Union and in France. The first successful electron-positron collisions in the U.S. were obtained in 1970 with the Cambridge Electron Accelerator. Although the start has been quite slow, the highlights of the field, namely the discovery of the Ψ/J particle, belong to the American collider SPEAR of Stanford. Burt Richter and Sam Ting have been awarded the 1976 Nobel Prize for physics for this discovery.

The development of hadron-hadron, namely proton-proton or proton-antiproton colliders, has proceeded much more slowly, mainly because of the higher energies at which colliding beams become effective and of more subtle technical reasons, the so-called Liouville theorem. They were developed at CERN, in Europe, and to a lesser extent in the Soviet Union. The first proton-proton collisions were observed in 1971 at the CERN-Intersecting Storage Rings, the ISR. The first proton-antiproton collisions (somehow the equivalent of the electron-positron colliders) were observed again at CERN, in 1981 at the SPS-collider. It is a few weeks ago that the great news of the successful operation of the TeV1 proton-antiproton collider at Fermilab has broken out, extending to the U.S. the field which CERN had made its own for almost fifteen years.

Energy of collisions has also grown considerably with time. It was 62 GeV in the center of mass for the ISR, it has reached 900 GeV at the SPS-Collider and it is now 1600 GeV at Fermilab. In comparison, the largest electron-positron machine under construction, namely LEP2, will barely achieve 200 GeV. However, quarks, rather than protons, are relevant in hadron collisions and, therefore, only 1/5 to 1/10 of the energy of the collision is useful. In spite of the large nominal difference, LEP2 and TeV1 are complementary machines and they will explore comparable energy scales. It is the complementarity between the European and U.S. programs which is of great importance to the field as a whole.

The third possibility, namely collisions between electrons and protons, is under construction in Germany, with a revolutionary machine called HERA, in which 800 GeV protons collide with 30 GeV electrons. The realization of this machine has been made possible by an unprecedented scheme of international collaborative effort. Although DESY is and remains a German laboratory, Italy is providing for 50% of the superconducting magnets, France is making the focussing quadrupoles, Canada is building the accelerating system, Holland the controls, etc. Money and know-how are extensively pooled in order to build such a very large and complicated set of accelerators. To my view, this is a model for the future, and it must be observed with great interest as an example for future enterprises.

In order to reach even higher energies and in the expectation that also beyond LEP2 and TeV1 some new phenomena are likely to occur, new initiatives are widely discussed. It should be stressed, however, that there is no "exact" prediction if and at which energy new phenomena to complete the picture of matter and of forces are to be found.

Most fundamental and long awaited discoveries, like, for instance, the so-called Higgs particle, may even come out from already existing machines. On the other hand, the alternative that even at the highest possible energies nothing really new may happen cannot be excluded. The "high risk" nature of each individual high energy physics initiative is self evident. Nevertheless, we have no other way of finding it out, except the traditional method of following the path of ever-increasing accelerator energies.

Production of new particles of higher masses and their related phenomena are inevitably associated to smaller observational probabilities. This is a very familiar effect. Going from atomic to nuclear and from nuclear to constituents physics, we have experienced an enormous overall drop in the rate of occurrence. Heavier members of particle "families" need not only higher energies but also a larger number of collisions in order to be observed.

In future hadron colliders, the event rate limitation of present detectors, rather than energy, will eventually set a limit to the mass domain which can be explored. Limitations are due to the use of gas detectors for imaging and accurate localizaton of tracks, radiation damage of scintillation counters and silicon detectors and the speed of computer processors to select the good events.

For instance, at the CERN Collider, a $Z \rightarrow e^{+} + e^{-}$ event occurs at the rate of one every billion interactions. In the case of a hypothetical Z-like particle of 3 TeV produced by a 15 TeV collider, the fraction of good events will drop to about one in a trillion of all events! If as many as ten million collisions are "processed" every second, the good event rate cannot exceed one every day.

Our discovery of the W and Z particles was particularly easy because of their unique and spectacular signature and because we knew where and what to look for. This is no longer so for the next steps, for which neither the energy nor the signature are precisely known. Many of the signatures which we want to search in the new energy domain, like, for instance, the Higgs or supersymmetric particles, are rather elusive, and an immense amount of data processing is necessary in order to identify processes occurring at a level from one every ten billion to few trillion of all events. There is a very significant chance that important phenomena may become masked by the huge number of "ordinary" collisions and that the unexpected physics may be missed.

A hypothetical 40 TeV collider with ten millions events/sec will have an impact somehow "equivalent" to the one of the CERN collider with the one thousand events/sec., much too small to be of practical interest for true and very rare high energy phenomena. To the extent that we believe that, for the present, the collider has an adequate luminosity, by the time we achieve 40 TeV we must be able to handle in excess of half a billion interactions each second! For comparison, the present CERN-UA1 detector has an operational limit at one hundred thousand interactions/second. Clearly, in order to exploit the SSC, we need radically new types of detectors.

Electron-positron colliders of energies larger than what is possible in LEP and which are necessarily linear colliders instead are not affected by detector limitations, since the total event rate is very low and almost every event is good. Event identification poses, therefore, relatively little or no problem. Although in principle, quark-quark and electron-positron collisions have similar couplings and therefore the same new processes should occur in both cases, the absence of the huge total event rate makes electron-positron colliders very attractive and detector construction easier. Unfortunately, we are not quite ready to construct such machines which still need more detailed design studies and the experimental confirmation of several fundamental assumptions, most of which will probably be provided by SLC. Its first operation in less than two years will no doubt be a very significant event in our field.

Thus, we face the dilemma: should the next European initiative be a proton or an electron collider? In Europe, studies on both alternatives are actively pursued. It is widely believed there that, in view of the length of time needed in order to launch realistically either the proton in the U.S. or the electron initiatives in Europe, an intermediate and relatively modest phase of hadron collisions in the LEP tunnel would give an excellent chance of not losing the interest of the taxpayers in the discoveries in HEP and of making smooth and gradual progress in the field. This phase should not appear as an attempt to compete with the "ultimate" world collider at highest energies and luminosities, either with electrons or with protons. These views are strongly supported by the European community of physicists, including many of the U.S. users at CERN.

The rapid realization of the LHC is today primarily a matter of money. If resources were to be available, one could construct it and operate it with a few years of delay from the beginning of LEP. How much money? Assume a single hadron ring added along the 27 km of electron machine under construction. This ring is 1/3 of SSC in length and only half of the magnets. Roughly, this is a factor 6 reduction over the SSC accelerator components, presently estimated to be about $1 billion. Estimates based on the HERA magnet costs from industry, and assuming a factor two reduction from these unit prices because of the huge quantity, gives approximately twice this estimate, namely $250 million. Therefore, a proton-antiproton machine of 1/3 of the SSC energy and $(1/3)^2 \approx 1/10$ of the luminosity can be built for under $300 million.

The LEP tunnel with additional hadron ring (and a field of 8 Tesla capable of storing particles at about 7500 GeV) will permit a broad spectrum of interesting and complementary investigations:

1) Electron-positron collider at 200 GeV.
2) Proton-antiproton collisions with 15,000 GeV in the center of mass and an event rate of 10 million events/sec.
3) an e-p option at 10 times the energy of HERA.

I believe that it is only natural that at CERN scientists wish to continue to work in the field of hadron colliders in which they have been actively working in the last fifteen years. LHC is not an alternative to the SSC that we all would like to see built. It is an intermediate step which we believe is worth building and exploiting in the way toward the largest energies.

PANEL 1 DISCUSSION

Mr. **Fuqua**. Thank you very much, Dr. Rubbia.

I think you've touched on it, and I'd like to inquire of both of you, that given the current level of theoretical understanding, is the SSC the next logical step for high energy physics to take, and, alternatively, maybe a smaller step, such as the large hadron collider would be a more appropriate level?

Dr. **Schopper**. Well, I think that based on the present knowledge, one believes that something new must happen in the range of about 1 TeV. And as Professor Rubbia said, to produce 1 TeV collisions between quarks, you'll need at least 6 times, maybe 10 times higher energies for protons to produce these energies.

Whether there's anything new beyond this mass range, nobody knows. Of course in the past we have learned that penetrating a new energy regime has always brought new surprises. And that's really what interests us. I mean, we penetrate into the unknown, and want to find completely new phenomena. Therefore, one can only extrapolate from the past saying that the larger the energy range is you have before you, the more likely it is to find new phenomena. But I think there can be no guarantee.

Dr. **Rubbia**. That's exactly what I said.

Mr. **Fuqua**. I thought you had answered that fairly well in your own statement. Have you had to adjust in CERN your research programs to accommodate the cost of LEP, or have you had to shut down any facilities or lay off people or reduce your running time?

Dr. **Schopper**. Indeed, in order to accommodate LEP in a constant budget we had to stop several facilities which were still producing good physics, but we had to make choices and we had to set priorities. And, for instance, we had to close down the so-called ISR, the only proton-proton collider in the world. We had to cut down several experimental facilities like BEBC, the large European bubble chamber, and many other things.

So, indeed we had to reduce the program by making choices. We did not have to lay off people, which in the European context is almost impossible anyway. But on the contrary, we needed people to build LEP. So what we had to do is we had to create an enormous internal mobility, moving people, redeploying people from other projects, and moving them to LEP.

Mr. **Fuqua**. There was a recent report, I understand, that made a recommendation to the British Government that they reduce their funding by about 25 percent by the end of this decade. What effect is that going to have? Do you have any other CERN members that are contemplating such action or is that view shared by—or the British recommendation of the British Government, is that shared by some of the other governments? (See Appendix 2.)

Dr. **Schopfer**. Well, this was a suggestion by a committee and chaired by Sir John Kendrew, which was endorsed by the Science and Engineering Research Council, and was presented to the Government. At present, the Government is discussing this report. It's not clear yet what the conclusion of the British Government will be. It will probably take another couple of months before the Brit-sh Government will come up with a proposal.

What happened was that the British Government has consulted other member states, and so far I can only say that the reaction corresponds with what indeed the Kendrew report itself says. He says that high energy physics is an exciting field, it's worthwhile to be followed up, to be supported. And the Kendrew report even suggests to the British Government itself to continue to support that field.

So, the question which comes up is rather not a programmatic one, but rather a question of efficiency, the question is to an organization like CERN which is now 33, 34 years old, is it possible to introduce some efficiencies there, to have some streamlining, to reduce personnel costs? So, probably the question would rather go in this direction and not concern so much the program as such.

Mr. MINETA. Mr. Chairman.

Mr. FUQUA. Mr. Mineta.

Mr. MINETA. Would you yield for a moment?

Mr. FUQUA. Certainly.

Mr. MINETA. Is the Kendrew report saying that they want to build their own capability of some kind within the United Kingdom and so therefore let us cut back on our commitment to CERN?

Dr. SCHOPPER. No, definitely not. I think I might mention one particular British difficulty; one might ask, "Why does all this come in Great Britain?" The difficulty is that the CERN budget is financed out of the budget of the Science and Engineering Research Council.

Now, according to our rules, the contributions of a member state has to be paid in Swiss francs, and is calculated according to the gross national product of that state. What happened was that the gross national product in Britain went up; we used data 3 or 4 years old a few years back because there were no statistics. So, the GNP in Great Britain went up, and the pound/sterling relative to the Swiss franc went down. So, from 1983 to 1984, Britain had to pay 30 percent more from one year to the next in pound/sterling, and that money had to be found inside the Science and Engineering Research Council. So, other sciences had to be cut and CERN didn't profit from it.

So, the way the CERN contribution is financed, in that it is particular there, and that is part of the problem.

Mr. FUQUA. Mr. Barton.

Mr. BARTON. Thank you, Mr. Chairman. I have kind of a general question for both of you. Dr. Rubbia indicated that an alternative might be a collider that costs less than $300 million and has a power of somewhere, I'm going to guess, six to nine TeV's, something like that. On the other hand, both of you mentioned in testimony you may want some colliders that go as high as 40 TeV.

I mean, how high do we have to go before you scientists decide that you've got the power that you need? I mean, 100 TeV? I mean, if you were in our position and had to make a determination of which level to fund and how much power to give you, would you want low power now and wait for a high energy 40 TeV down the road, or go with the 20 TeV that we have?

I mean, we're not scientists, at least I'm not, and I'm confused.

Dr. RUBBIA. Could I perhaps try to add to your confusion? The situation at CERN is, in a certain sense, is simpler and clearer because the tunnel already exists. Therefore, the question is, if you want to build a collider which is dedicated, which is built from the beginning to be a collider—and let me remind you that the machine, the SPS which we used so far, is a machine which has been—modified starting from an ordinary accelerator to become a collider if you want to build yourself a new collider dedicated, since the previous one has been successful and everything else, then obviously you will think it natural to put such a device in the tunnel of LEP, which is the largest tunnel you have. And indeed such an idea has occurred from the beginning of the design.

And you'll try to find out the best—the highest field magnets you can find, and the maximum is somewhere between 8 and 10 Telsa, depending on the technology. And that will naturally set the energy of the project anywhere between 10 and 15 TeV colliding beam energies, therefore about one-third of the energy of the projected SSC.

So, the energy in the LEP is an input parameter coming from the existence of the tunnel and from the basic technology which you have attained. Then you ask yourself, "Given the fact that energy is what it is, can you do something useful with it?" And the answer is that the energy you have will be about 10 times the energy of the present TeV I. And you would believe that in absence of a project of the magnitude like the SSC, which everybody would prefer to see happening on a short time scale, then that machine could make a full contribution to science as an intermediate step. It's slightly modest in resources, it does not offer as many facilities as the SSC would provide neither in terms of number experiments nor in terms of collisions, nor in terms of energy. But taken in absolute terms, it may be a worthwhile initiative. It certainly is the largest initiative that you could think of in terms of the framework of—which has all the problems which I mentioned a minute ago.

In the case of the SSC you start from free ground. You have a choice of the site, you have a choice of the technology, and therefore you can choose the energy which you feel is ultimate, so to speak, which is unconstrained by the presence of devices. And you reach a conclusion that the largest energy machine you can build is probably three times larger than one one has at CERN. And, of course, you put two rings in there so you get more luminosity, more events. And events, as I tried to point out, are very important. The number of events is as important as the energy.

Now, in itself the presence of a proton ring and of an electron ring in the LEP tunnel offers not only the possibility of doing hadron-hadron collisions, but also the possibility of an electron-proton collisions. In itself this is a very justifiable alternative, even if it would turn out that the proton-proton is not competitive with the SSC it certainly is not taken at face value.

There is still the electron-proton option open as a possibility. And Europe is investing massively now in HERA, which is a pioneering machine in the electron-proton collision system. And to have a second generation electron-proton machine at 10 times the energy in the LEP tunnel, available to the worldwide community, is certainly in itself a very valuable solution.

So, in a certain sense, adding a hadron ring to the LEP tunnel is—inevitable, if you like. And the only reason why the thing will not happen is either because it will turn out that it is not competitive with a scientific point of view, or because the financial situation—which is difficult in Europe—are such as to prevent oneself from investing the money which is acquired from constructing those manuals.

In the case of the SSC, on the contrary, one is trying to do the best possible job. I hope I've——

Mr. **Barton**. Well, you still——

Dr. **Schopper**. Can I answer the question in a more general way, because what you're asking really is, will it forever go on? What is coming after SSC? Are these high energy physicists never satisfied?

Well, I think the situation is the following. Unfortunately, there are some fundamental laws of nature which say the deeper you want to penetrate into the microcosmos, the more powerful microscopes, let me say, you need, which are our accelerators—which, by the way, is not so different from the other frontier which is space. The deeper you want to penetrate into space, also the better equipment you need. So in that sense it will not finish.

But, on the other hand, what we are trying to do is to achieve savings by modern technology, and therefore, in a way, to get along with "smaller" equipment than before. Also costwise, let me tell you, LEP is 27 kilometers around compared to our previous project SPS which was 6½ kilometers. However, the cost of LEP was the same as the previous machine. In a way I think that's also true for the SPS—I'm sorry, for the SSC, where per GeV, the cost is much lower than for all previous accelerators.

So in a way, yes, it will never end so long as humanity is curious to explore what's going on. But by using new technologies, new developments, we try to do it at a reduced price.

Mr. **Barton**. Mr. Chairman, I'd like unanimous consent to ask one more question, if I could.

Mr. **Fuqua**. Go ahead. We'll stretch the minute.

Mr. **Barton**. Assuming that we decide in this country to build the SSC, there were two magnet designs; a low field design of 3 Tesla and a high field design of 6 Tesla. The magnet design selection committee has chosen the high field design, the 6 Tesla design.

But should we want to go to a more powerful microscope, as you so well put it, down the road, which of those two designs could we most easily increase in the power; the low field 3 Tesla design or the high field 6 Tesla design?

Dr. **Schopper**. To my opinion, I think that's not a criterion to choose between the two, because in whatever you choose now one will have magnets with higher fields. So, I think that's not a criterion on which you can base your decision on which——

Mr. **Barton**. Well, it's my understanding that the designs are different enough that if should we decide to try to go to 40 TeV, that there would be some differences about which of those designs could be increased to that power. But again, I'm not a scientist, so I may be incorrect on that.

Dr. Rubbia, would you like to try to answer that?

Dr. **Rubbia**. Well, I mean, the answer that was already more or less given by Professor Schopper, when he said that when building LEP, you tried to build the largest possible tunnel, which offers you a possibility of improvement in size. On the other hand, it is also clear that the cost of the tunnel is a small term with respect to the costs of the other machine. So, you should look into which kind of time scale you're considering to build the next machine.

If you want to build the next machine in the next 10 years, then to have an existing tunnel, an existing laboratory may be very healthy. If the next step will come in 50 years, then I wouldn't worry very much whether that space will be used or not.

Mr. **Barton**. So you're for the largest tunnel, and then later technology will put the more powerful magnets in the larger tunnel.

Dr. **Rubbia**. I think the larger tunnel is—we have learned in Europe that the largest tunnel is an asset. In the case of LEP, it is an asset.

Mr. **Barton**. Thank you, Mr. Chairman.

Mr. **Fuqua**. Mr. Stallings.

Mr. **Stallings**. Thank you, Mr. Chairman. Professor Schopper, why has the preeminence of the United States in high energy physics been seriously challenged by CERN in the last few years?

Dr. **Schopper**. Look, I think it's very hard to determine and define preeminence. I think our field is so diversified that you always can find a certain part of the field where one laboratory is ahead and in another part another laboratory is ahead. So, as far as physics is really concerned, it's very hard to define it.

You can say that that continent has preeminence where the largest energy is available. Even that is a bad criterion, but you could say now, since Fermilab has the highest energies the United States s back. But I think it's not the right kind of criterion.

I think what is important is that both continents are actively in- olved in that field, that the programs are complementary, and hat whatever machines are available, they are open to physicists rom the other continent. That's fortunately the situation that we re in now.

Mr. **Stallings**. Thank you. Professor Rubbia, will the SSC be op- imized for a particular kind of research to prevent any duplication f cost or effort with other planned "new generation accelerators?"

Dr. **Rubbia**. I think the answer is yes, and I'd like to qualify it. he hadron collider in that tunnel is, I tried to explain, a different pe. I don't believe that anybody in the world will go ahead and uild a—in the present circumstances—a duplicate of the SSC. owever, I believe that if you were to go ahead and build the SSC, en people from all over the world will come and ask to be al- wed to use it.

So, by building the SSC you will have a predominance in this rticular field that you've chosen to be predominant with, and it ll dominate the world scene. Now, I am deeply convinced there ll not be two SSC's in high energy physics, and I think there ould not be two. In fact, I was trying to explain in my testimony at if you were to go ahead for the large proton-proton collider, it uld be more appropriate for Europe to maintain complementar- and try to think in terms of something else. And I tried to point that there is another machine which is in a more distant ure, but is still a very exciting machine, which is an electron- itron machine.

We have now had complementarity, as was pointed out, between TeV I—which is a proton machine—and LEP, which is an electron-positron machine. It seems to me that if this country will continue to—the line of hadron colliders, of building what I would call a superlarge TeV I, which is the SSC, it will be normal for Europe to continue the LEP line, and try to see where there is a possibility of developing even more powerful electron-positron collisions.

Now, in the same way—however, the TeV I is now being shared now by European physicists and American physicists. And LEP is largely dominated by the presence of the U.S. participants. I believe the trend will continue—testify to all the benefits of the scientific community as a whole. But I really think the important thing is not to win, it's to participate.

Mr. STALLINGS. Thank you, Mr. Chairman.

Mr. FUQUA. Mr. Fawell.

Mr. FAWELL. I have no questions.

Mr. FUQUA. Mr. Slaughter.

Mr. SLAUGHTER. No questions, Mr. Chairman.

Mr. FUQUA. Mr. Mineta.

Mr. MINETA. Thank you, Mr. Chairman. Professor Schopper, we've had the privilege of being the beneficiary of your fine hospitality there. It's good to have you here. I'm just wondering, given the competition for funding and for the number of extremely costly, high energy projects, if the United States goes ahead with the planning and the construction of the SSC, what that would do in terms of your large hadron collider. Would that effect your plans one way or the other?

Dr. SCHOPPER. Well, it's very difficult to say, since I said there are various elements that are still missing before a decision will be taken. I completely agree with what Dr. Rubbia said. I think certainly duplication will not be acceptable. I do not think that if you would go ahead with the SSC, that Europe would build a similar machine, or let's say a factor of two lower intensity.

Then one possibility would be to go for electron-proton collisions in the LEP tunnel, or maybe do something completely different. I do not know.

Mr. MINETA. Well, is it a question of who gets there first?

Dr. SCHOPPER. I don't think so, because as I said several times now, the uniqueness of these facilities implies that they should be open to physicists from all over the world. So, I think if the SSC would be built, I hope that physicists from Europe will be able to participate there, and vice versa with whatever we do in Europe that Americans will be welcome there.

Therefore, if you have in the same group, Americans, Europeans and other people, the question of who gets there first is not so relevant anymore.

Mr. MINETA. What do you think is going to be the result of the Kendrew report? Will the United Kingdom adopt it given its submission as a report now, or——

Dr. SCHOPPER. Well, let me point out again that the Kendrew report has two parts. The first 85 pages say very extremely and strongly that high energy physics should be continued and they recommend to the British Government to support this field for the future. So, I hope this part of the Kendrew report will be followed.

As far as the reduction of budget is concerned, as I said before, I think it concerns less the program than more questions of economy of personnel budgets and so on. And there I do not know what the outcome will be.

Mr. **Mineta**. Do you think there are any other countries contemplating actions similar to what's being recommended in the Kendrew report to the United Kingdom?

Dr. **Schopper**. Again, fortunately all the other countries said, as a program, as a field, one has to continue to support certain high energy physics. As far as efficiencies are concerned, some other countries might join them. But it's more a technical, financial question and not so much a criticism against the field.

Mr. **Mineta**. And you haven't heard of any other countries that may be contemplating similar action?

Dr. **Schopper**. As far as cost effectiveness is concerned, yes, some other countries are considering it also.

Mr. **Mineta**. But is anyone considering lowering their contribution to CERN and following something similar to the Kendrew report?

Dr. **Schopper**. Well, what some other countries are also considering is, for instance, a question of personnel costs. I mean, this means going now into technical detail. CERN is an international organization so there are questions like what should be the salary of an international organization compared to domestic organizations, and so on. So the arguments are more of this kind and do not concern the criticisms of the field. Nobody has criticized so far the program as such.

Mr. **Mineta**. Thank you very much. Thank you, Mr. Chairman.

Mr. **Fuqua**. Thank you. Mr. Bruce.

Mr. **Bruce**. No questions, Mr. Chairman.

Mr. **Stallings**. Mr. Chairman, may I ask one more?

Mr. **Fuqua**. Certainly, Mr. Stallings.

Mr. **Stallings**. Mr. Rubbia, what happens if the United States does not build the SSC? Will it be built elsewhere?

Dr. **Rubbia**. What I said, I don't think there's anyone—my own personal feeling is that I don't believe Europe will ever be able to, under the present circumstances, get even close to anything like the dimensions and the size of the SSC.

Professor Schopper has mentioned the construction of LEP. LEP is a $300 million, $400 million, $500 million affair for the machine, and then probably a few hundred million dollars in addition for the experiments. And he has stressed the European community financially to the limits. It's very hard today to do anything else but to work for LEP in Europe. LEP has absorbed a tremendous amount of free energy which was present in the system, I believe—as much as one can imagine in the present level of funding that the community can take.

I can also believe that the level of funding in Europe at present s not such as to assume that it will go up tremendously. The previous remarks are certainly to the direction of feeling optimistic. If ou feel optimistic, you feel that the budget will stay constant.

Therefore, there is no room within the European system for a hing like this. I do not know whether the Soviet Union may decide o start up a program of accelerators of a large magnitude. Let me

remind you that there is a machine which is built in Novosobir
which is a superconducting accelerator. And it may well be th
that may lead to something——

Dr. Schopper. So sorry, not Novosibirsk, Sepukhov.

Dr. Rabbia. Sepukhov, I beg your pardon. So, I don't believe th
there will be many initiatives anywhere else in the magnitude
SSC. And because of limitations, not because of interest of the s
entists not having that, I'm sure that a lot of people all over t
world, which will look forward to the physics you can get out of t
SSC, simply cannot afford it.

And therefore, if this country does not decide to go ahead wi
the SSC, then there will be a bit of a vaccum, which I think w
have to be filled up somehow differently.

Mr. Stallings. That's the next question. What happens to hi
energy physics then if we don't build, and if it's not built, do
just sort of go on hold until some new technology comes on-lin

Dr. Rubbia. I think that will lead to a differentiation of techn
ogies. New ideas will come along, new other attempts will
brought in and it will take longer. I believe, however, that the fie
somehow would find its own senses one way or the other. I mea
we have a lot of bright people in the field. We still get most of t
good young scientists joining the field of elementary particle ph
ics, and they will certainly, together with us, figure out somethi
But I think it will be a shock, it will be a slow down, it will be
loss in the progress which will not be negligible.

Mr. Stallings. Thank you, Mr. Chairman.

Dr. Rubbia. It is not only for the United States, at least it's tr
also for the rest of the world.

Mr. Fuqua. Thank you, Mr. Stallings. Dr. Schopper, we tha
you for sharing your time with us. Dr. Rubbia, we're very delight
to have you back again with us, and we hope to visit you someti
again at CERN. Have a very successful trip back home.

[Panel 1 questions and answers for the record follow:]

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Geneva 19 December, 1985

Dear Mr. Fuqua,

In reply to your request of 27 November 1985 my answers to your two questions are as follows.

Question 1 - History of the Large Hadron Collider

Already at the design stage of LEP in 1980-1981 it was decided to make both the size of tunnel and its circumference as large as possible in order to leave room for the installation of another ring of accelerating magnets in the tunnel in due course. This idea was subsequently taken up by the European Committee for Future Accelerators ECFA who organized a Workshop in March 1984 in Lausanne, Switzerland on "Large Hadron Collider in the LEP Tunnel". The various possible options for such an accelerator were also presented at the Workshop on "Future Perspectives in High Energy Physics" held at the KEK Laboratory in Japan in May 1984, organized by the International Committee for Future Accelerators (ICFA). It is important to stress that the Large Hadron Collider is not a project but simply a set of options for machines of various energies depending on the strength of the magnet field which is chosen. The CERN Council has set up a Working Group under the Chairmanship of Professor Carlo Rubbia to study these options. This Group will report in June 1987 but it will consider also other possibilities, e.g. colliding linear accelerators.

In parallel, technical development work on superconducting magnets is going on at CERN in collaboration with industry.

Question 2 - US Participation

Preliminary discussions on possible collaboration between Europe and the USA on a future accelerator in Europe have taken place in the Long-term Planning Sub-Panel of the Versailles Working Group on High Energy Physics. However no specific suggestions have yet been made, especially as the nature of the next European accelerator is not yet clear, and much research and development work remains to be done especially in the fields of superconducting magnets and RF cavities. In order to keep this field of science healthy a limited number of accelerators or colliding facilities are essential, however.

It was agreed that one should aim at a coherent complementary programme in the US and in Europe strengthening the already now existing mutual participation in the respective programmes. The present practice to contribute to experimental facilities could be extended to contributions for construction of accelerators.

In this frame US participation and collaboration in any future Large Hadron Collider project at CERN would be most welcome. New ways of bringing about such a collaboration would have to be found to give a proper basis for joint work. For example one might envisage a special status at CERN for those countries wishing to participate in the construction of a new project in the LEP tunnel.

I hope that these two replies are sufficient to answer your questions, but I would be glad to provide any further information if you so wish.

Yours sincerely,

Herwig Schopper

Mr. **Fuqua**. Our next witness is Dr. Jack Sandweiss, professor of physics at Yale University and Chairman of the Department of Energy's High Energy Physics Advisory Panel. Dr. Sandweiss, we're very pleased to have you with us this afternoon.

Dr. **Sandweiss**. Well, thank you very much, Mr. Chairman and members of the subcommittee. I'm very pleased to have the opportunity to be here today and to share with you some of the thinking which was done as a result of the 1985 summer study. And I would like to proceed, in order to save time, by using the viewgraph, if I may.

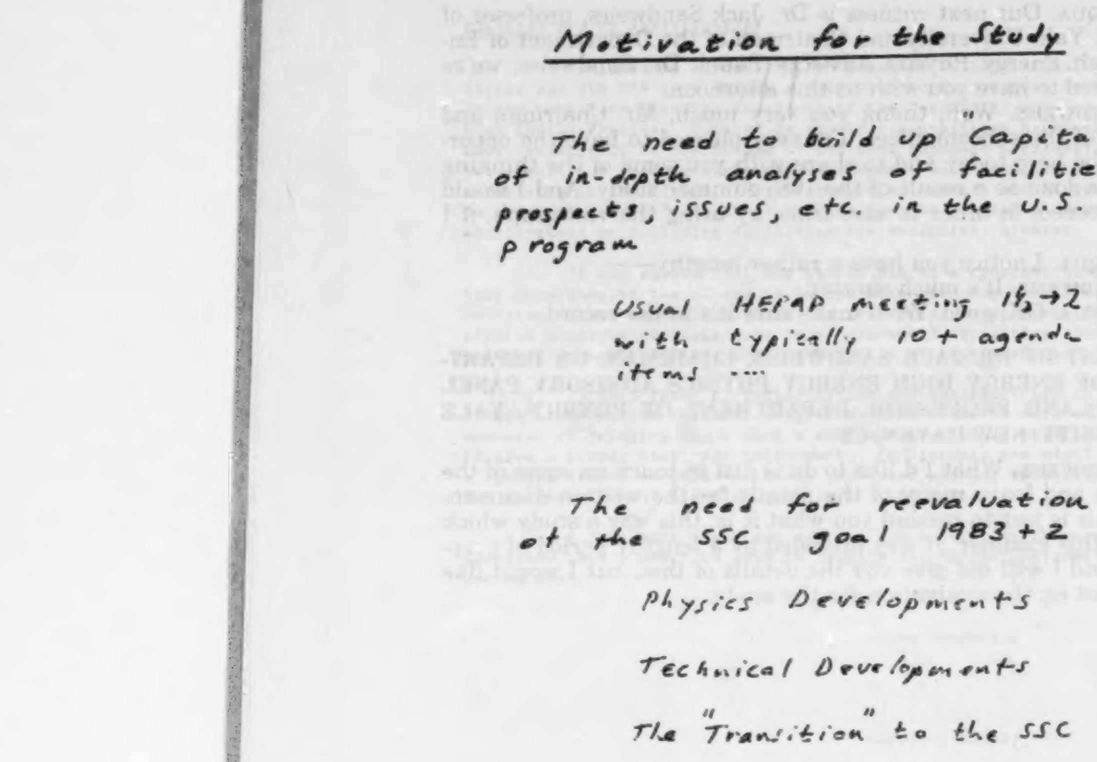
Mr. **Fuqua**. I notice you have a rather lengthy——

Dr. **Sandweiss**. It's much shorter.

Mr. **Fuqua**. OK, good. We'll make sure it's in the record.

STATEMENT OF DR. JACK SANDWEISS, CHAIRMAN, U.S DEPARTMENT OF ENERGY HIGH ENERGY PHYSICS ADVISORY PANEL [HEPAP] AND PROFESSOR, DEPARTMENT OF PHYSICS, YALE UNIVERSITY, NEW HAVEN, CT

Dr. **Sandweiss**. What I'd like to do is just to touch on some of the highlights and leave many of the details for the written documentation. This is just to remind you what it is; this was a study which was held this summer. It was preceded by a lengthy period of preparation, and I will not give you the details of that, but I would like to comment on the motivation for the study.



Motivation for the Study

The need to build up "Capital" of in-depth analyses of facilities, prospects, issues, etc. in the U.S. program

Usual HEPAP meeting 1½ → 2 days with typically 10+ agenda items ....

The need for reevaluation of the SSC goal 1983 + 2

Physics Developments

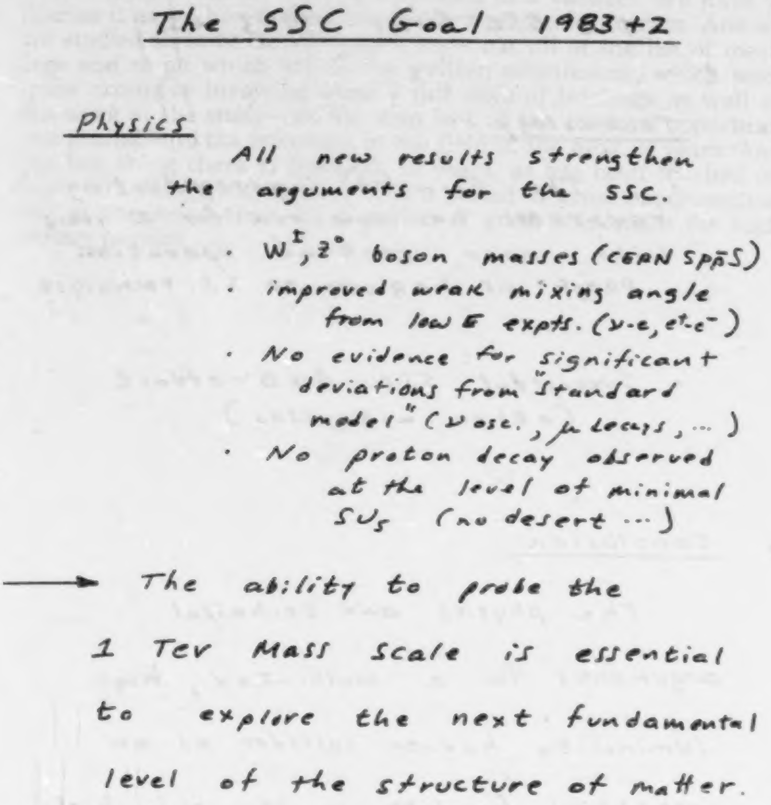
Technical Developments

The "Transition" to the SSC

SLIDE 1

The study was held really for two reasons. One reason was the need for HEPAP to spend some time building up its capital, so to speak, of indepth analyses of facilities prospects and the issues in the U.S. program. The usual HEPAP meeting is 1½ to 2 days. There are usually more than 10 items on the agenda. That is not conducive to indepth analysis.

The second reason was the need to look again at this all important role that we had previously recommended of the SSC. I would just remind you that the first recommendation from HEPAP was in 1983, and I choose to write 1985 as 1983 plus two. In the intervening years there have been physics developments, technical developments, and we wanted to look as well onto the issue of how might we make a transition from the current program into a program in which the SSC was present. And so, we wanted to look at that.



The SSC Goal 1983+2

Physics

All new results strengthen the arguments for the SSC.

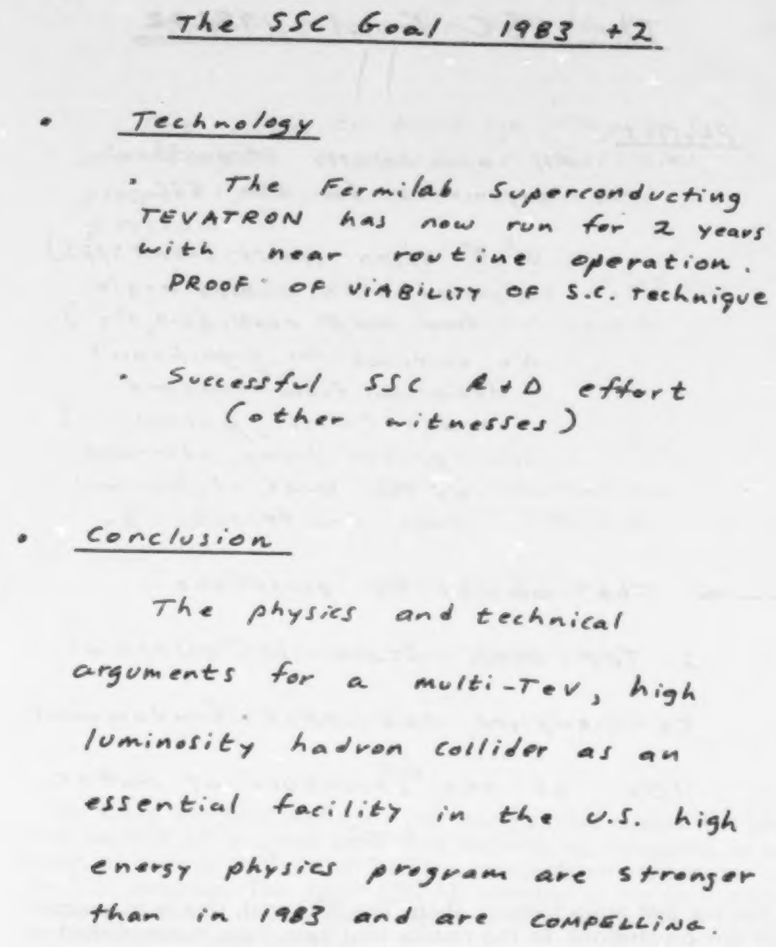
- $W^{\pm}, Z^0$ boson masses (CERN $Sp\bar{p}S$)
- improved weak mixing angle from low E expts. (ν-e, e^+-e^-)
- No evidence for significant deviations from "Standard model" (ν osc., μ decays, ...)
- No proton decay observed at the level of minimal SU_5 (no desert ...)

→ The ability to probe the 1 TeV Mass Scale is essential to explore the next fundamental level of the structure of matter.

SLIDE 2

Let me just jump forward then. The SSC goal, this is to summarize our conclusions. In the results that have been accomplished in physics, one way to summarize them— I won't go through the individual items, they're in the report—but you can summarize them by saying that all new results strengthen the physics arguments for the SSC. And we concluded, and I'm being very brief here, but we concluded that in fact the ability to probe the 1 TeV mass scale is essential to explore the next fundamental level of the structure matter. And the physics goal of the SSC is stronger now than it was in 1983. And I think, as has been said previously, that is nearly a unanimous point of view in the field.

Another aspect of that goal, of course, is the technology. In the intervening 2 years, the Fermilab superconducting accelerator has operated in a near routine style. And people have spoken about that earlier. That is a wonderful achievement, but it's also proof of the viability of the technique of superconducting magnets.



The SSC Goal 1983 + 2

- Technology
  - The Fermilab Superconducting TEVATRON has now run for 2 years with near routine operation. PROOF OF VIABILITY OF S.C. technique
  - Successful SSC R + D effort (other witnesses)
- Conclusion

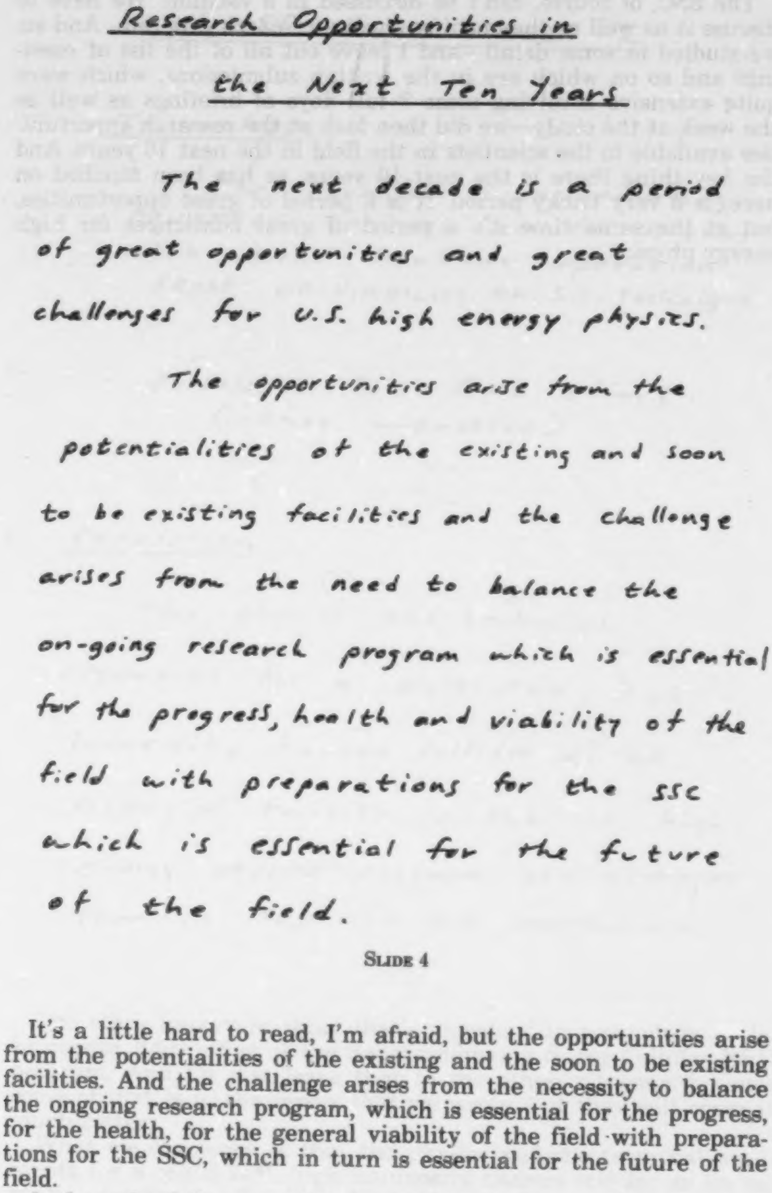
The physics and technical arguments for a multi-TeV, high luminosity hadron collider as an essential facility in the U.S. high energy physics program are stronger than in 1983 and are COMPELLING.

SLIDE 3

The other important thing that's happened in technology is the successful R&D effort of the Superconducting Super Collider R&D program. And I'll just leave that to the other witnesses because some of that is in the report that we wrote, but they will cover it much better.

What we concluded is that the physics and the technical arguments for a multi-TeV, high luminosity hadron collider as an essential facility in the U.S. High Energy Physics Program, are stronger than in 1983, and are compelling. So, these are, so to speak, the broad pictures that were reviewed and remain that way.

The SSC, of course, can't be discussed in a vacuum. We have to discuss it as well as the ongoing physics research program. And so, we studied in some detail—and I leave out all of the list of meetings and so on which are in the written submissions, which were quite extensive involving some 7 full days of briefings as well as the week at the study—we did then look at the research opportunities available to the scientists in the field in the next 10 years. And the key thing there is the next 10 years, as has been touched on here, is a very tricky period. It is a period of great opportunities, but at the same time it's a period of great challenges for high energy physics.



Research Opportunities in the Next Ten Years

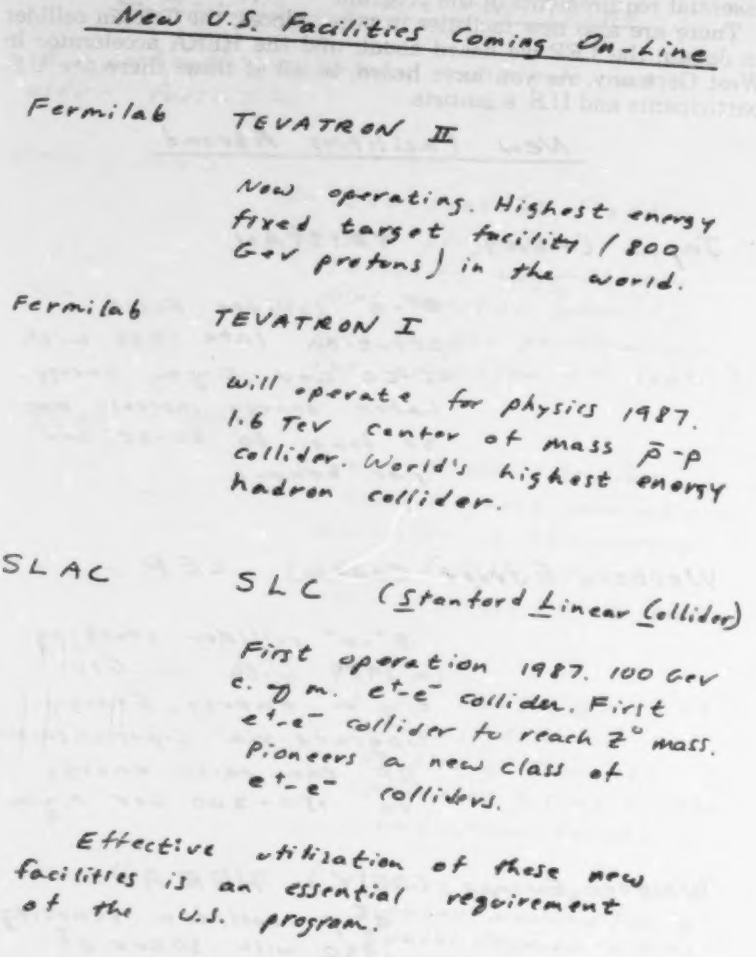
The next decade is a period of great opportunities and great challenges for U.S. high energy physics.

The opportunities arise from the potentialities of the existing and soon to be existing facilities and the challenge arises from the need to balance the on-going research program which is essential for the progress, health and viability of the field with preparations for the SSC which is essential for the future of the field.

SLIDE 4

It's a little hard to read, I'm afraid, but the opportunities arise from the potentialities of the existing and the soon to be existing facilities. And the challenge arises from the necessity to balance the ongoing research program, which is essential for the progress, for the health, for the general viability of the field with preparations for the SSC, which in turn is essential for the future of the field.

And so, the following is how to balance those two things as best as one can. I have listed some of the facilities. I will just flip through them very fast to remind you that one of the new ones, of course, is the Fermilab TeV-II, which has been operating now for 2 years. It's the highest energy fixed target accelerator, superconducting accelerator.



New U.S. Facilities Coming On-Line

Fermilab TEVATRON II

Now operating. Highest energy fixed target facility (800 GeV protons) in the world.

Fermilab TEVATRON I

will operate for physics 1987. 1.6 TeV center of mass $\bar{p}$-p collider. World's highest energy hadron collider.

SLAC SLC (Stanford Linear Collider)

First operation 1987. 100 GeV c. of m. e^+-e^- collider. First e^+-e^- collider to reach Z^0 mass. Pioneers a new class of e^+-e^- colliders.

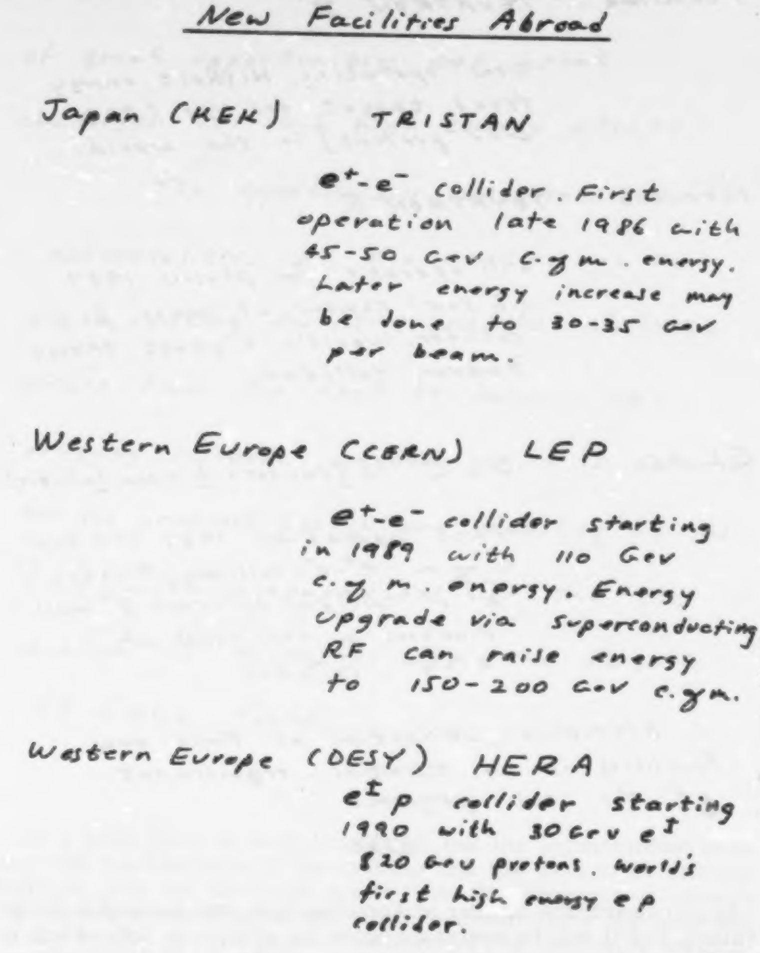
Effective utilization of these new facilities is an essential requirement of the U.S. program.

SLIDE 5

As you heard, the collider at Fermilab that just succeeded in operating, and it will be operating again for physics in 1987, when it will then be the world's highest energy collider. At SLAC, the Stanford linear collider will have its first operation in 1987. It will reach 100 GeV center of mass energy, and it will be thus the first e^+ e^- collider to reach the important point of the Z° mass, and it also pioneers a new class of electron-positron colliders.

One thing that was universally agreed on at the study was that the effective utilization of these new facilities that have been built in the U.S. program at such cost and effort is, in fact, one of the essential requirements of the program.

There are also new facilities in other places; the Tristan collider in Japan; the LEP we heard about; and the HERA accelerator in West Germany. As you have heard, in all of these there are U.S. participants and U.S. scientists.



New Facilities Abroad

Japan (KEK) TRISTAN

e^+-e^- collider. First operation late 1986 with 45-50 Gev c. of m. energy. Later energy increase may be done to 30-35 Gev per beam.

Western Europe (CERN) LEP

e^+-e^- collider starting in 1989 with 110 Gev c. of m. energy. Energy upgrade via superconducting RF can raise energy to 150-200 Gev c. of m.

Western Europe (DESY) HERA

$e^\pm$ p collider starting 1990 with 30 Gev $e^\pm$ 820 Gev protons. World's first high energy e p collider.

SLIDE 6

There are also older facilities, which I won't dwell on, but Brookhaven, AGS, SLAC, HEP, all of these were studied in some detail by us. And good programs exist in all of them. They're viable, they're very productive.

Existing U.S. Facilities

Important programs continue at older facilities.

BNL AGS

30 Gev protons, fixed target program.
(Intensity upgrade via AGS booster planned, will improve performance for precision h.e. expts.)

SLAC PEP

e^+-e^- collider 30 Gev c. of m. Highest available luminosity in this energy region. Possible upgrade could increase lum. by 3→4.

SLAC SPEAR

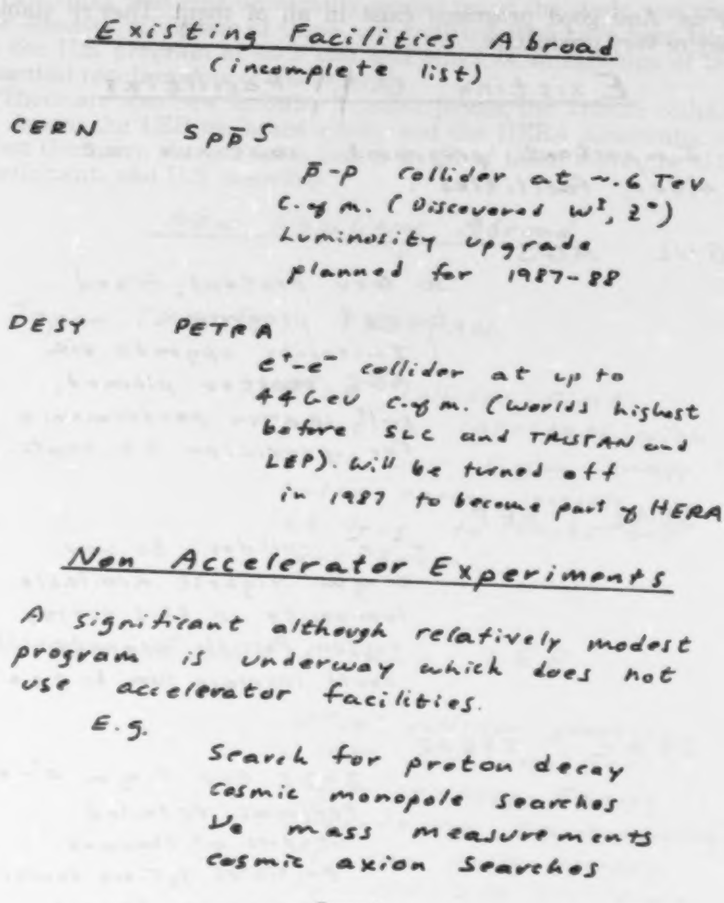
3-7.5 Gev c. of m. e^+-e^-
Performs detailed studies of charmed particles. 1/3 Time Synchro. radiation Source.

Cornell CESR

10-12 Gev c. of m. e^+e^-
premier machine for "b" quark. Upgrade in prog.

SLIDE 7

There are also existing facilities abroad; the CERN collider, which is so famous, the first p̄p collider; the PETRA accelerator at DESY, which incidentally will turn off in 1987 and become part of the HERA accelerator that you heard about, the ep collider.



Existing Facilities Abroad

(incomplete list)

CERN $Sp\bar{p}S$

$\bar{p}$-p collider at ~.6 TeV
c. of m. (Discovered $W^{\pm}$, Z^{0})
Luminosity upgrade
planned for 1987-88

DESY PETRA

e^{+}-e^{-} collider at up to
44 GeV c. of m. (worlds highest
before SLC and TRISTAN and
LEP). Will be turned off
in 1987 to become part of HERA

Non Accelerator Experiments

A significant although relatively modest program is underway which does not use accelerator facilities.

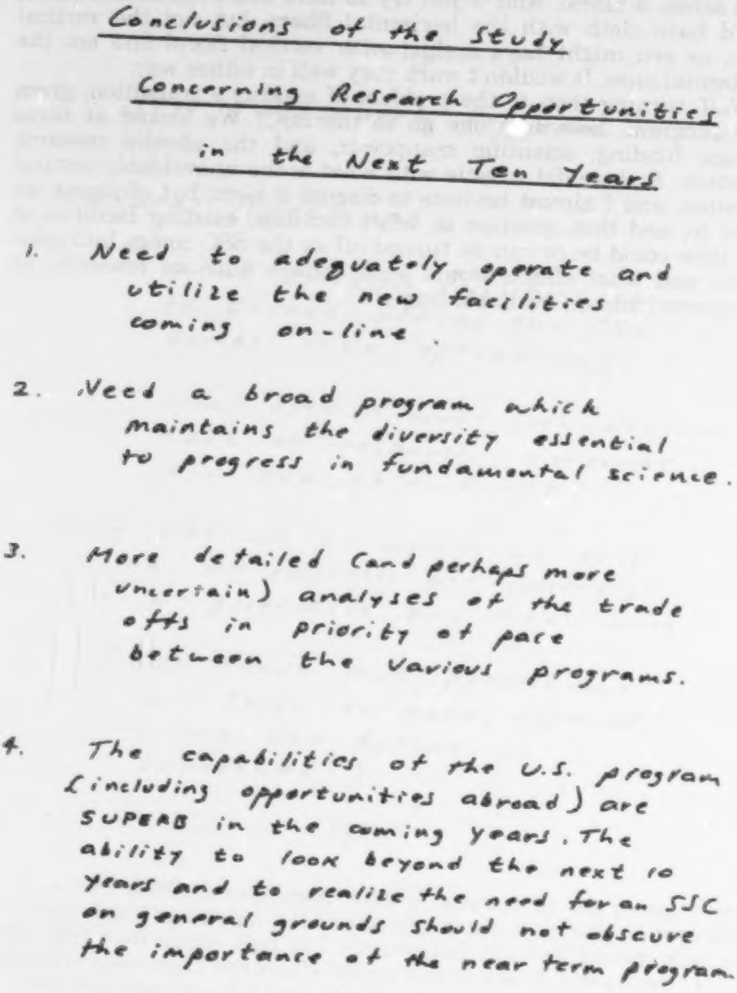
E.g.

Search for proton decay
Cosmic monopole Searches
ν_e mass measurements
Cosmic axion Searches

SLIDE 8

And then finally I would just mention that there is a significant, although relatively modest, program in research that doesn't use accelerators, that uses nonaccelerator techniques such as searching for proton decay and various other things. Now, all of these, too, were reviewed by us. We broke up into six working groups which had briefings and presentations, and prepared position papers prior to the weeklong meeting.

Let me then jump rapidly to the conclusions of the study concerning the research opportunities in the next 10 years. These are fundamentally four. One is the need to effectively operate and utilize the new facilities coming on-line. Two is something that I think is very important to emphasize, and that is that whatever we do, we must maintain in the program an essential diversity in order to have progress. That no committee is smart enough to really know how to focus one's scientific efforts too finely. We must have a broad program which maintains the essential diversity.



Conclusions of the Study
Concerning Research Opportunities
in the Next Ten Years

1. Need to adequately operate and utilize the new facilities coming on-line.

2. Need a broad program which maintains the diversity essential to progress in fundamental science.

3. More detailed (and perhaps more uncertain) analyses of the trade offs in priority of pace between the various programs.

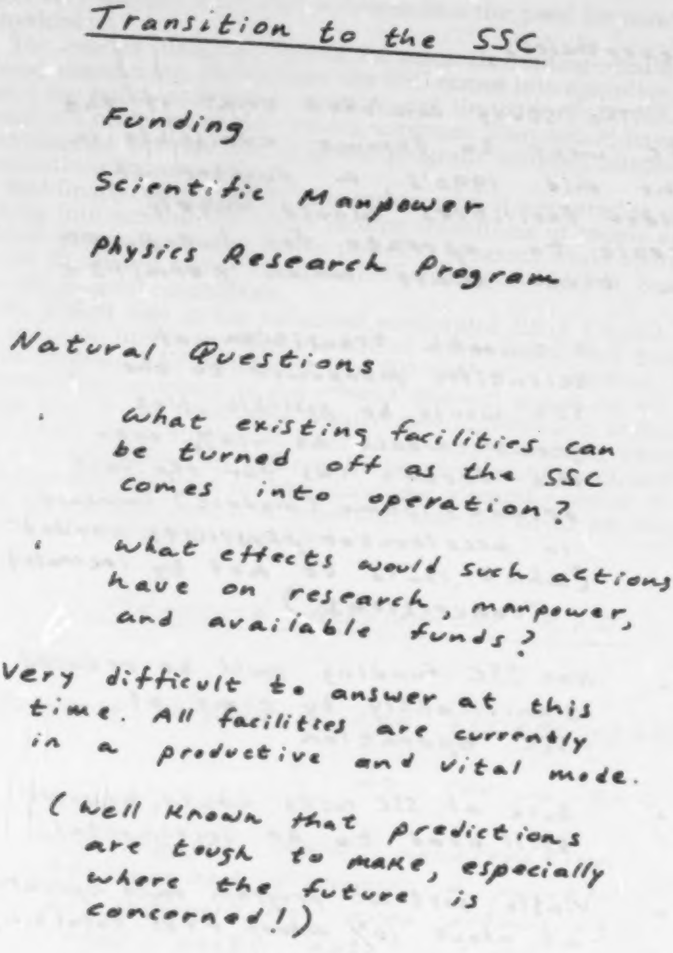
4. The capabilities of the U.S. program (including opportunities abroad) are SUPERB in the coming years. The ability to look beyond the next 10 years and to realize the need for an SSC on general grounds should not obscure the importance of the near term program.

SLIDE 9

And then, finally, we made a lot more detailed and perhaps more uncertain analyses of the trade-offs which hopefully will be useful. I won't discuss them further. Some of them are in the report.

The last thing I'd like to comment on is the following. The ca
bilities of the U.S. program, including opportunities abroad,
superb in the coming years. The ability to look beyond the next
years and to realize the need for an SSC on general grounds sho
not obscure the importance of the near term program. That is, it
in a sense, a fabric. And if you try to have one without the oth
you'd have cloth with the horizontal fibers, but not the verti
ones, or you might have a shirt with vertical fibers and not t
horizontal ones. It wouldn't work very well in either way.

Well, turning then to the problem of making a transition, giv
this program, how does one go to the SSC? We looked at thr
things; funding, scientific manpower, and the physics resear
question. And we did wrestle with what is the unavoidable natu
question, and I almost hesitate to discuss it here, but of course
have to, and that question is, what facilities, existing facilities
the time could be or can be turned off as the SSC comes into op
ation, and what effects would such actions have on research,
manpower, and on available funds?



Transition to the SSC

Funding

Scientific Manpower

Physics Research Program

Natural Questions

- What existing facilities can be turned off as the SSC comes into operation?
- What effects would such actions have on research, manpower, and available funds?

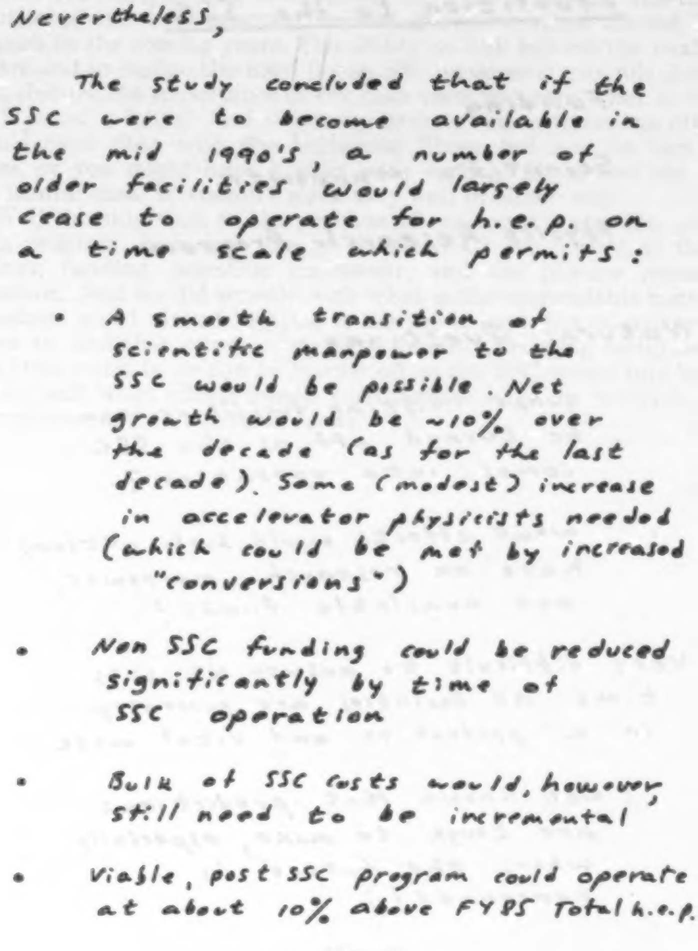
Very difficult to answer at this time. All facilities are currently in a productive and vital mode.

(Well known that predictions are tough to make, especially where the future is concerned!)

Slide 10

It's very difficult to answer such a question at the present time, looking into the future. All the facilities are currently in a productive and vital mode. And as I commented, it's well known that predictions are tough, especially where the future is concerned.

Nevertheless, we did our best to do that. And I think although one cannot be sure about the details, certain generalities are likely to be correct, and they are the following. We concluded that if the SSC were to become available in the mid-1990's, a number of older facilities would largely cease to operate for high energy physics on a time scale which permits the following.



Nevertheless,

The study concluded that if the SSC were to become available in the mid 1990's, a number of older facilities would largely cease to operate for h.e.p. on a time scale which permits:

- A smooth transition of scientific manpower to the SSC would be possible. Net growth would be ~10% over the decade (as for the last decade). Some (modest) increase in accelerator physicists needed (which could be met by increased "conversions")
- Non SSC funding could be reduced significantly by time of SSC operation
- Bulk of SSC costs would, however, still need to be incremental
- Viable, post SSC program could operate at about 10% above FY85 Total h.e.p.

SLIDE 11

One, it permits a smooth transition of scientific manpower to t
SSC. We estimated that the growth in manpower would just
what it has been, about 1 percent per year, and that can fluctua
Basically it's a more or less standard manpower. No addition
manpower has to be added to the field beyond what it natural
does.

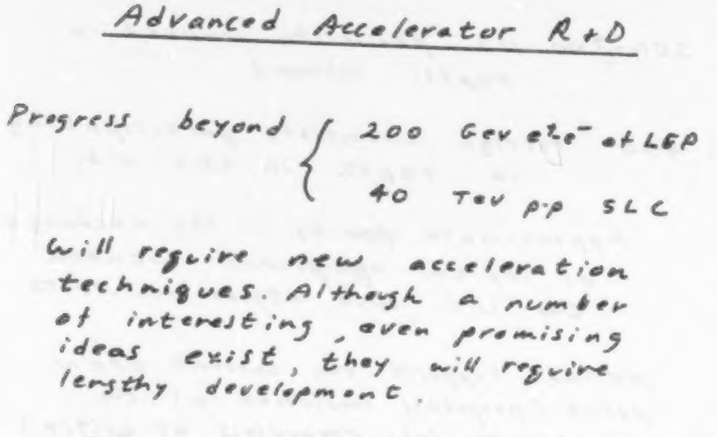
We did notice that some increase in accelerator physicists wou
be necessary, but accelerator physicists are a small fraction of t
field. And all of them, or nearly all of them arise from convert
experimental physicists. And if you just change that rate of conve

sion very slightly, one could accommodate the need for accelerator physicists.

The non-SSC funding—that is the research funding—could be reduced significantly by the time the SSC comes into operation. However, the bulk—and this is obvious—but the bulk of the SSC costs could not come out of the ongoing program. They would have to be incremental because the ongoing program couldn't support the entire thing by any means.

And finally, after the SSC was constructed, it appeared to us that taking into account the above factors; transitions of people and research programs, that a viable post-SSC program could operate at about 10 percent higher than the 1985 total level of effort. So, those are the general conclusions.

We looked also at the advanced accelerator R&D. I won't dwell on this now, just to say that the SSC of course is a 40 TeV center of mass proposal, LEP is ultimately a 300 GeV, $e^+ e^-$ machine. To go beyond these numbers at the present moment is a thing we don't know how to do. That will require new acceleration techniques. And there are a number of interesting, even promising ideas, but it's very clear that they will require lengthy development, and that development will have to take place over a lengthy period of time. And during that time, it is important that the advanced accelerator R&D be vigorously supported.



Advanced Accelerator R+D

Progress beyond { 200 GeV e^+e^- at LEP
40 TeV p-p SLC

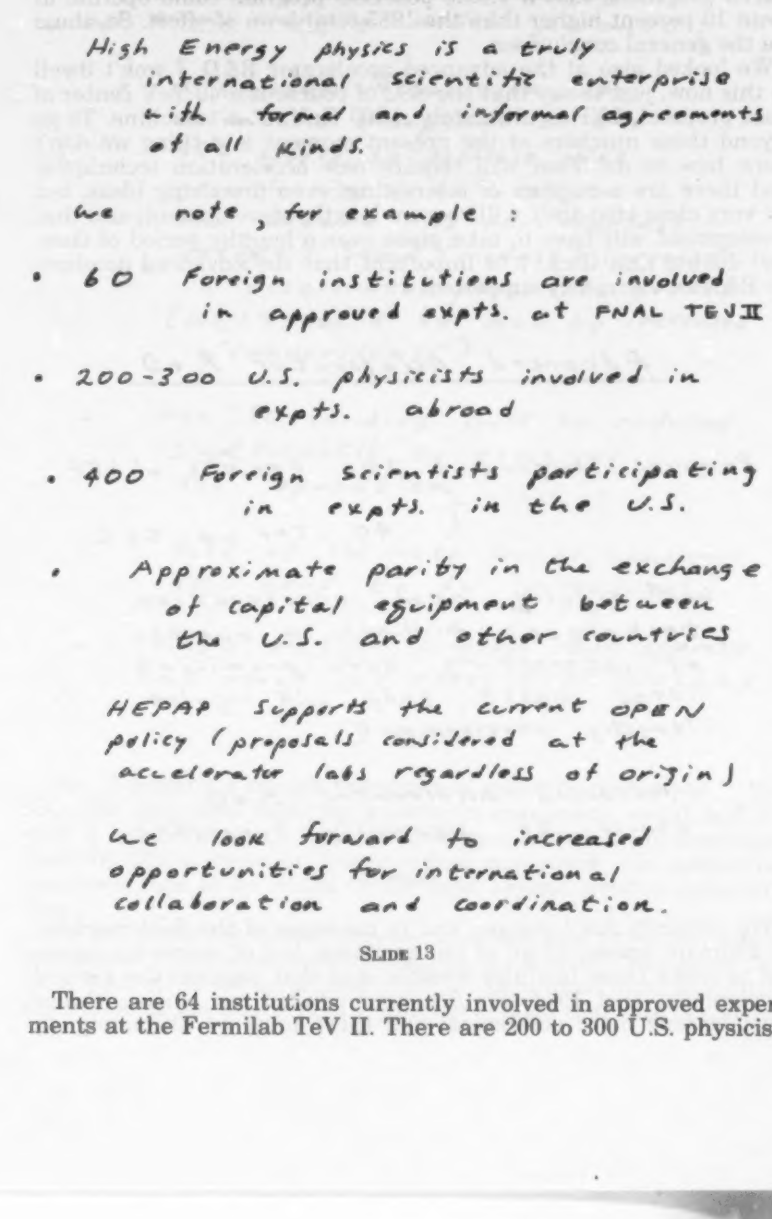
Will require new acceleration techniques. Although a number of interesting, even promising ideas exist, they will require lengthy development.

Advanced accelerator R+D should be vigorously supported.

SLIDE 12

We certainly don't see any end in the sense of the field reaching an ultimate answer to all of the questions, but of course it's essential to make these facilities feasible, and that requires the kind of development that Professor Schopper pointed out earlier; things must become more economical and there must be ultimately all these new techniques, as the superconductivity is the new technique that makes the SSC possible.

On international collaboration I just thought I'd show you some numbers we collected. I agree with what other people have said—we agreed, I shouldn't say I agreed. But it might be interesting for you to know that this field is currently extremely international. That's been expressed before, but here are some interesting numbers.



International Collaboration

High Energy physics is a truly international scientific enterprise with formal and informal agreements of all kinds.

We note, for example:

- 60 Foreign institutions are involved in approved expts. at FNAL TEV II
- 200-300 U.S. physicists involved in expts. abroad
- 400 Foreign scientists participating in expts. in the U.S.
- Approximate parity in the exchange of capital equipment between the U.S. and other countries

HEPAP supports the current OPEN policy (proposals considered at the accelerator labs regardless of origin)

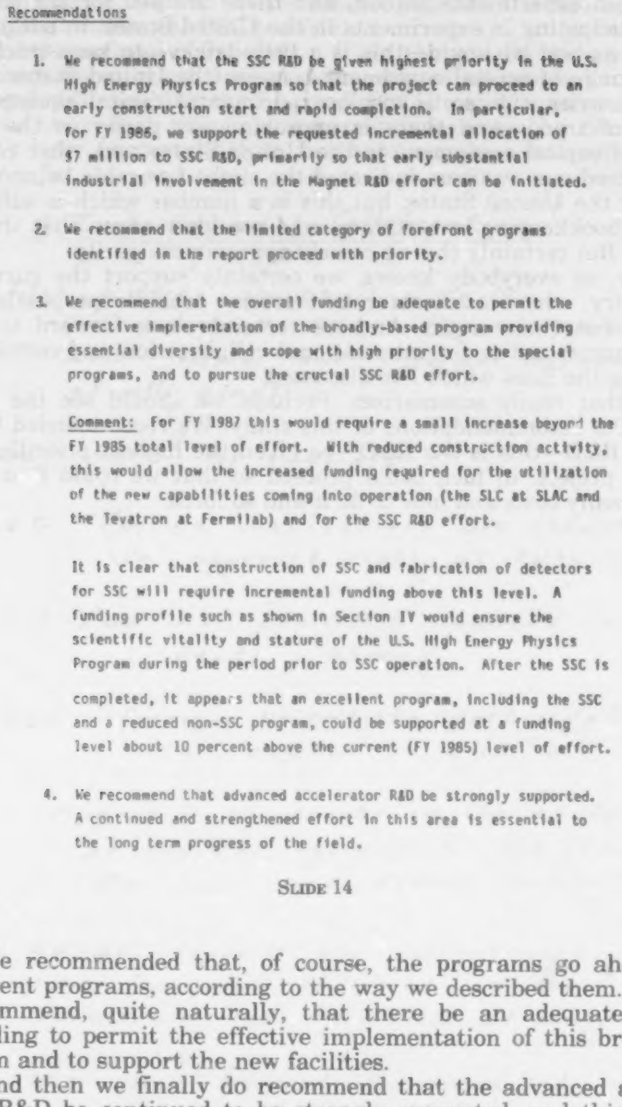
We look forward to increased opportunities for international collaboration and coordination.

Slide 13

There are 64 institutions currently involved in approved experiments at the Fermilab TeV II. There are 200 to 300 U.S. physicists involved in experiments abroad, and there are 400 foreign scientists participating in experiments in the United States. In addition, we tried as best we could—this is a little tricky—to keep track of the exchange of capital equipment between the United States and other countries; the, so to speak, experimental capital equipment balance of trade. And there is approximately parity in the exchange of capital equipment in the United States and other countries. Indeed our numbers indicated the slight favorable balance of trade for the United States, but this is a number which is subject to some bookkeeping uncertainty, so I wouldn't argue that that's the case. But certainly there's clearly approximate parity.

Finally, as everybody knows, we certainly support the current open policy, where accelerator laboratories consider proposals no matter what their origin. And we certainly look forward to increased opportunities for international collaboration and coordination along the lines which I've discussed.

Well, that really summarizes. Perhaps we should see the last slide of the recommendations of this study. We recommended that the SSC R&D—this is the R&D—be given the highest priorities so that the project, in fact, could proceed so that we could find out what it really costs and how to do it and so forth.



Recommendations

1. We recommend that the SSC R&D be given highest priority in the U.S. High Energy Physics Program so that the project can proceed to an early construction start and rapid completion. In particular, for FY 1986, we support the requested incremental allocation of $7 million to SSC R&D, primarily so that early substantial industrial involvement in the Magnet R&D effort can be initiated.

2. We recommend that the limited category of forefront programs identified in the report proceed with priority.

3. We recommend that the overall funding be adequate to permit the effective implerentation of the broadly-based program providing essential diversity and scope with high priority to the special programs, and to pursue the crucial SSC R&D effort.

   Comment: For FY 1987 this would require a small increase beyond the FY 1985 total level of effort. With reduced construction activity, this would allow the increased funding required for the utilization of the new capabilities coming into operation (the SLC at SLAC and the Tevatron at Fermilab) and for the SSC R&D effort.

   It is clear that construction of SSC and fabrication of detectors for SSC will require incremental funding above this level. A funding profile such as shown in Section IV would ensure the scientific vitality and stature of the U.S. High Energy Physics Program during the period prior to SSC operation. After the SSC is completed, it appears that an excellent program, including the SSC and a reduced non-SSC program, could be supported at a funding level about 10 percent above the current (FY 1985) level of effort.

4. We recommend that advanced accelerator R&D be strongly supported. A continued and strengthened effort in this area is essential to the long term progress of the field.

SLIDE 14

We recommended that, of course, the programs go ahead, the current programs, according to the way we described them. And we recommend, quite naturally, that there be an adequate overall funding to permit the effective implementation of this broad program and to support the new facilities.

And then we finally do recommend that the advanced accelerator R&D be continued to be strongly supported, and this will be needed for the long term help of the program.

Well, perhaps this is a good time to stop. If there are questions I'll be happy to respond to them.

[The prepared statement of Dr. Sandweiss follows:]

A Written Statement by Jack Sandweiss to the Subcommittee on Energy Development and Applications of the House Science and Technology Committee

OCTOBER 29, 1985

I. Introduction

The High Energy Physics Advisory Panel (HEPAP) held a week long study of the U.S. high energy physics program during July 2 to July 8, 1985. The study was held so that HEPAP could make an in-depth review of the program, focusing on the next ten years. The usual 1½ to 2 day meetings do not permit in-depth study of the issues and in formulating its advice HEPAP must necessarily draw upon its "capital" of background and knowledge. One principal motivation of the study was thus the desire to build up that capital. The second principal motivation for the study grew out of our recognition of the central role of the SSC project in planning for the U.S. program and accordingly a substantial part of the study was devoted to a reevaluation of the SSC goal and to an analysis of how a transition to an "SSC era" might be accomplished.

II. Preparation for the Study

The study was preceded by a major information gathering activity which took place during the spring of 1985. Seven working groups, consisting of HEPAP members and outside consultants, were formed to organize presentations and to prepare position papers for the study. These are listed in table I below, with their associated HEPAP members.

1985 HEPAP Summer Study

Working Groups

1. e^+e^- Facilities (C. Baltay, G. Feldman, S. Ting)
2. Fixed-Target Facilities (P. Koehler, R. Palmer, B. Winstein)
3. Proton-Antiproton Colliders and Electron-Proton Colliders (M. Einhorn, J. Peoples)
4. SSC (J. D. Jackson, R. Siemann, S. Wojcicki)
5. Accelerator Operations and Advanced Accelerator R&D (H. Edwards, H. Grunder, R. Palmer)
6. Non-Accelerator Physics and Interfaces with Other Fields (R. Adair, M. Creutz)
7. Organization, Budget Scenarios, and Manpower (C. Baltay, P. Koehler, J. Sandweiss)

In all, six days of briefings were held for presentations and discussions organized by the working groups and one day was devoted to presentations by, and discussions with, the directors (or their representatives) of the high energy physics laboratories around the world. These are summarized in table II below.

Table II

Information Gathering Meetings for 1985 HEPAP Summer Study

Date and Location	Topics
April 22,23, 1985 Brookhaven National Laboratory Upton, Long Island, N.Y.	Accelerator Operations and Advanced Accelerator R&D Non Accelerator Physics and Interfaces with Other Fields
April 24, 1985 National Academy of Sciences Washington, D.C.	U.S. and Foreign Laboratory Directors Meeting with HEPAP
May 8, 9, 1985 Fermi National Accelerator Laboratory Batavia, Illinois	Proton-Antiproton and Electron-Proton Colliders Fixed Target Facilities
May 23,24, 1985 Stanford Linear Accelerator Center Stanford, California	Electron-Positron Colliders SSC R&D

III. The Superconducting Super Collider

Two years have now passed since the original HEPAP recommendation on the SSC. Thus, one should examine physics developments since that time to see whether there have been any significant changes in our understanding of the physical world to warrant any modifications of the original recommendation. The core of the argument for the SSC was the belief that the Standard Model (the unified electroweak theory, plus QCD), even though remarkably successful in providing an elegant description of all known phenomena, cannot be the final answer. Furthermore, on the basis of both the general arguments and specific models, it was believed that the capability to explore mass scales in the TeV region is necessary to provide significant new clues about the nature of a more comprehensive theory. The Standard Model does not explain many key features such as particle masses and requires many ad hoc parameters.

The last two years have strengthened appreciably the confidence in the Standard Model. More abundant samples of W and Z bosons from the CERN $p\bar{p}$ Collider have allowed one to conclude with much higher precision that the masses of W and Z bosons and their decay modes are in conformity with the Standard Model. Simultaneously, the improved accuracy of the neutrino electron scattering experiments and of the e^+e^- annihilation experiments has provided improved values of the weak mixing angle parameter which is in agreement with the value derived from the W mass. In addition, the study of jets at the high energy collider machines confirms in a semi-quantitative way the predictions of perturbative QCD.

Evidence for deviations from the Standard Model has been looked for in various areas. Experiments looking for neutrino oscillations, supersymmetric particles, and rare muon decay modes are some examples of such searches. No significant deviations from the Standard Model have been found.

Finally, the mysterious Higgs particle still has not been found in spite of additional searches. This spinless particle (or family of particles), arising out of the Higgs mechanism is postulated to explain the symmetry breaking in the electroweak theory, and its discovery is one way to resolve the difficulties which would otherwise arise in the Standard Model. The model, however, gives no detailed predictions as to its mass, except the general requirement that the mass cannot be much in excess of 1 TeV. Alternatively, if Higgs particle(s) do not exist with mass below about 1 TeV, the electroweak interactions would have to become strong in the 1 TeV constituent center-of-mass range, leading to a wealth of new phenomena. Thus, the ability to probe the TeV mass region still appears to be required if this all-important question is to be solved.

The very important negative result from the proton decay search performed by the Irvine-Michigan-Brookhaven (IMB) group appears to rule out the simplest Grand Unification scheme, the minimal SU_5 model. This particular solution predicted a desert (i.e. absence) of new phenomena over a very wide energy range (up to 10^{15} GeV). The fact that a different solution seems to be required if grand unification is to be realized reinforces the belief that a wealth of new phenomena may be expected in the TeV range.

Finally, the trend which began several years ago regarding the interplay of many ideas in physics and cosmology has been growing stronger. The cosmological arguments for investigating higher energies are quite powerful. One is even more confident today than two years ago that SSC will shed significant new light on the early evolution of our universe.

On the technical side, there are two broad developments which are relevant to the SSC. The first of these is the successful operation of the Fermilab Tevatron, the first high energy superconducting accelerator. This machine achieved first beam just before the HEPAP meeting of July 1983. Since that time it has operated routinely at 800 GeV and has demonstrated beyond question the viability of the superconducting technique. The second broad development has been the successful R and D program carried out under the leadership and coordination of the Central Design Group. The impressive progress of this R and D strongly supports our confidence in the soundness of the SSC concept and in the basic "picture" of the accelerator as provided in the earlier Reference Designs Report. HEPAP was impressed with the need to provide increased SSC R and D funding so that a completed SSC by the mid 1990's would be a possibility. Such increased support is also necessary to involve industry substantially in the design and fabrication of the SSC components at an early stage so that completion of the SSC by the mid 1990's will be a realistic goal. Since other witnesses at today's hearing will provide more complete information on the SSC R and D, I do not give any further discussion of this important area here.

IV. Research Opportunities in the Next Ten Years

The next decade is a period in which the U.S. high energy physics program faces both great opportunities and great challenges. The opportunities come from the new facilities which are becoming available now and in the next few years and which will be described below. The challenge comes from the simultaneous need to exploit those facilities and to maintain a vigorous and balanced program while at the same time preparing for the next step, the SSC. It is essential for the viability and health of the U.S. program to do both.

The superconducting Tevatron at the Fermi National Accelerator Laboratory (Fermilab) is operating at an energy of 800 GeV and provides the highest energy fixed-target facility in the world. The Fermilab Collider will become operational in 1987 and will be the world's highest energy hadron collider, extending the energy range to 1.8 TeV from 0.6 TeV available now at the CERN S$\bar{p}$pS. The Stanford Linear Collider (SLC), which will come into operation in 1987 at the Stanford Linear Accelerator Center (SLAC), will be the first e^+e^- collider to reach the energy of the Z^0 and also represents a pioneering effort toward a new class of electron-positron colliders. The effective utilization of these new facilities is an essential requirement.

The physics opportunities also include major U.S. participation in research programs at new facilities abroad: at CERN, the Large Electron Proton (LEP) project will become operational in 1989, providing e^+e^- collisions initially in the Z^0 range and later at higher energies, up to 200 GeV in the center-of mass; in Japan, the TRISTAN project will become operational in 1987, providing e^+e^- collisions up to a center-of-mass energy of about 60 GeV. In West Germany, the Hadron Elektron Ring Anlage (HERA) project which is expected to begin operations in 1990, will provide e^+-p collisions up to center-of-mass energy above 300 GeV, opening new opportunities for research.

In addition to these new facilities there is a continuing program of important experiments at older facilities such as the Brookhaven AGS which provides intense proton beams up to 30 GeV for fixed target experiments and the SLAC PEP e^+-e^- collider with total energy of about 30 GeV. The research programs which could be carried out in the next ten years with these facilities are rich in potential for fundamental discovery, broad in scope, and form a complex, often interconnected pattern. Since research by definition involves the study of the unknown, it is difficult to evaluate research programs in advance. Experience has shown that many factors, some not always understood in advance, affect the productivity of a research effort. Unexpected results or unexpected connections, sometimes of great importance, can and do occur. It is primarily for these reasons that a healthy research program must be a broad program.

It is essential for the U.S. high energy physics program to continue to be a diverse effort with strong activities in each of the major avenues of the field.

The report of the summer study discusses each of the research programs in modest detail which would be inappropriate here. Copies of the report are, of course, available to interested individuals.
Within the context of a broad program which maintains an essential diversity, it is possible, however, to identify a limited category of experiments or programs which enter a new experimental regime in such a way as to have clear promise for new fundamental discoveries. Because of their intrinsic importance, because of the likely impact their results would have on the course of future research, and because of their importance to the U.S. program it is viewed as essential that such forefront efforts proceed in a timely fashion. This category includes the following major programs: the CDF and D0 projects at Tevatron I, the L3 program at LEP, the Mark II and SLD projects at the SLC, and CESR program at Cornell. The Panel also considers the smaller scale efforts involving studies of CP violation with kaons, high sensitivity studies of rare kaon decays, and certain parts of the non-accelerator program to be in this category.

We conclude this section by noting that by the end of the period under consideration, i.e. by the mid 1990's, many of the opportunities described above will have been realized, the older facilities will almost certainly not be operating for high energy physics and the newer facilities will be approaching the end of their first decade of operation. None of the facilities will permit the exploitation of the TeV mass range. It is for these reasons, of course, that the U.S. high energy physics community has placed such high priority on preparation for the SSC.

V. Transition to the Superconducting Super Collider

We are looking forward to the start of SSC construction in 1988 and an expected completion in 1994 after a 6-year construction period. In this Section, we describe a strong U.S. High Energy Physics Program and show how the transition to the SSC might proceed. We look at "snapshots" of the program at three distinct times: in 1987, before the start of SSC construction; in 1991, during the SSC construction; and finally, in 1995, after the SSC has been completed and its operation for experiments has begun. Obviously, there are uncertainties associated with anticipating the program 10 years in the future in a rapidly moving field such as High Energy Physics. The following is our expectation from today's vantage point.

A. Evolution of the Research Program

1. The Program in 1987

By this time, the new facilities presently under construction will be completed. This will be the start of the rich utilization of all of our facilities. At Fermilab, the Tevatron I $\bar{p}p$ collider will be in early operation with one detector. The Tevatron II fixed-target programs will be in full operation. At SLAC, the e^+e^- collider, SLC, will be in its initial operation and PEP will be in full operation. The lower energy e^+e^- collider, SPEAR, will be utilized about half-time for high energy physics. At Brookhaven, the AGS will be in full operation. The majority of AGS time will be devoted to high energy physics, with a small portion of the time used by the nuclear physics program studying heavy ion collisions. At Cornell, the newly upgraged e^+e^- collider, CESR, will be fully utilized. There will also be a number of U.S. groups working at non-U.S. facilities. Detectors for the e^+e^- collider, LEP, and the $e^\pm p$ collider, HERA, will be under fabrication, and there should be experiments running at the e^+e^- collider, TRISTAN, and the $p\bar{p}$ collider, the S$\bar{p}$pS. A variety of non-accelerator experiments will be taking data. A vigorous SSC R&D program in advance of construction will be in progress, both on the accelerator systems and the associated detectors. There will also be activity in advanced accelerator R&D.

2. The Program in 1991

By this time, we expect the SSC will be in the middle of its construction period. The construction of detectors for the SSC will be in full swing. At Fermilab, the collider will operate with both major detectors and the full complement of fixed-target facilities, including the Direct Neutral Lepton Facility, will be utilized, both for experiments and for providing test beams for detector development. At SLAC, the SLC will be in full operation. At Brookhaven, a high intensity AGS with a completed Booster will be utilized partially by the high energy physics program and partially by the nuclear physics heavy ion program. At Cornell, CESR will still be operating. There will also be U.S. groups taking data in experiments at LEP and TRISTAN. Experiments at HERA, with U.S. participation, will be starting up. A variety of non-accelerator experiments will be taking data. The activity in advanced accelerator R&D will be increasing.

3. The Program in 1995

By this time, we expect that the SSC will be in its early stages of operation with at least a partial complement of detectors. At Fermilab, we expect that the collider will be running with a mature program; the fixed-target facilities will be operating for an experimental program at a reduced level in addition to supplying test beams for new detector development. The SLC at SLAC will still be in operation. The AGS at Brookhaven is expected to be almost fully occupied as an injector for the heavy ion collider, RHIC, and as a fixed-target facility for the nuclear physics program and is not expected to be utilized significantly by the high energy physics program. U.S. groups will probably still be involved at LEP II and HERA, but the TRISTAN involvement is expected to be winding down. A variety of non-accelerator experiments will be taking data. We anticipate a vigorous program in advanced accelerator R&D at this time. It will be difficult to maintain a forefront U.S. program if the operation of the SSC is delayed beyond this time.

B. Funding Required for the High Energy Physics Program

An estimate has been compiled for a minimum budget required to carry out the program described in this report. For the pre-SSC program in FY 1987, these estimates are $435 million for operating, $90 million for equipment, $70 million for construction (for a total of $595 million non-SSC related) and $65 million for SSC R&D, for a total high energy physics budget from the DOE of $660 million. An additional $55 million is required from the National Science Foundation (all in FY 1987 dollars). For comparison, the FY 1985 High Energy Physics budget (converted to FY 1987 dollars) was $400 million in operating, $66 million in equipment, and $129 million in construction, (for a total of $595 million non-SSC related) and $23 million for SSC R&D, for a total DOE budget of $618 million, with an additional $46 million from the NSF. We note that while the total non-SSC related funds needed for FY 1987 are essentially the same as in FY 1985, the operating funds are up and the construction funds are down relative to FY 1985. This is necessary for the following reasons. Two of the major accelerator facilities of the High Energy Physics program will be coming into full operation by 1987. These unique state-of-the-art accelerators (SLC and Tevatron) are not only the mainstay of the High Energy Physics program but also prototypes for future higher energy accelerators. It is essential that incremental operating funds be provided for these facilities.

With these assumptions, the projection of the DOE High Energy Physics budget to FY 1995 is given in Table IV-1. Here the SSC construction, equipment, and operating costs from the SSC Reference Designs Study have been used. It can be seen that a substantial pulse of incremental funding over the FY 1987 level is required for the SSC construction for the FY 1988 to FY 1993 period. After this period, the funding required for the program, including the operation of the SSC, returns to within about 10 percent of the FY 1985 level. During the SSC construction period, the non-SSC part of the budget declines, reaching a reduced level of about $400 million by FY 1995. The SSC operating costs are expected to be $215 million with an additional $50 million in equipment funds and $15 million in accelerator improvement (AIP/GPP) funds, for a total high energy physics budget from the DOE of about $680 million in FY 1995 (in FY 1987 dollars).

C. Scientific Manpower

Current estimates indicate that the U.S. scientific manpower (Ph.D physicists or equivalent) working in high energy physics at the present time consists approximately of 1,150 experimentalists, 750 theorists, and 330 accelerator scientists. The number of experimentalists now occupied in carrying out the present program is not a bad match to the requirement of the program during the SSC construction period and the period after the start of SSC operation. We do, however, anticipate a scarcity of accelerator physicists during the SSC construction period. A need for a 20 to 30 percent increase in the number of accelerator scientists is anticipated. A vigorous program of training present high energy physics experimentalists and theorists in accelerator science is of high importance in the near future. In addition, efforts should be made to make a career in accelerator physics attractive to young physicists entering the field of high energy physics. We anticipate a flow of experimentalists and accelerator physicists from the present program to the program including the

SSC. We expect that in addition to the U.S. physicists, there will be a substantial number of non-U.S. experimentalists working at the SSC. This analysis shows that the existing high energy physics manpower, with an anticipated 10 percent growth over the next decade, can accomplish the program described in this report.

Table III

Projected High Energy Physics Budgets
1985 - 1995
(in units of millions of FY 1987 dollars)

	FY 85	FY 87	FY 91	FY 95
Non-SSC Program				
Operating*	400	435	410	350
Equipment	66	90	70	40
Construction	129	70	20	10
Total Non-SSC	595	595	500	400
SSC Program				
R&D	23	65	40	0
Construction			700	15
Equipment			130	50
Operating			30	215
Total SSC	23	65	900	280
Total DOE Program	618**	660	1400	680
NSF	46	55	48	48

* Includes University budgets, part of which will be spent on SSC Experiments.

**546 in FY 85 $

VI. Advanced Accelerator R&D

Progress in high energy physics accelerators is often shown in a "Livingston plot" which shows an exponential growth of energy with time. This growth has been achieved by an alternation between the development of a particular technology and the introduction of a new one.

The storage ring technique has been the key to the energy advances of the last decade. There are now many successful e^+e^- and hadron-hadron colliders. Two machines, Tevatron I and LEP, are under construction to be major facilities in the next decade. Such storage rings, however, appear to be reaching their ultimate energy. LEP is forced by synchrotron radiation considerations to a circumference of 27 km. The proposed SSC, because of magnetic field constraints, would have a circumference of approximately 100 km. These are at the limits of practical size.

Progress beyond the 200 GeV center-of-mass energy of LEP and 40 TeV center-of-mass energy of SSC will require new acceleration techniques. At this time, there are no practical ways to either avoid the synchrotron radiation in e^+e^- machines, nor to use economically significantly higher magnetic fields in proton rings. Linear colliders such as the SLC offer the possibilities of much higher energies for both electrons and protons, but the existing technology would be prohibitively expensive in or above the TeV range.

In response to this challenge, and following the recommendation of the HEPAP Subpanel on Accelerator Research and Development, the efforts to find new acceleration methods have been expanding. These efforts range from

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relatively modest extensions of technology to the exploration of new physical phenomena. The emphasis has been on exploring as wide a range of ideas as possible.

Much of this work has been of a theoretical or exploratory type. There seems to be no lack of ideas, though new ones are always welcome. More work is now needed on real experimental demonstration. This will require a significant increase in funding above its present level of approximately $7 million per year, an increase HEPAP strongly endorses.

The emphasis up to now has been on encouraging a wide range of new initiatives without being too critical about their application to a real collider design. This has been necessary. However, the time for such serious study has come. Within the next few years one or two ideas should be ready for more active and directed development toward a very high energy facility. Between $5 and $10 million per year may be required for this work, in addition to continued funding for the more speculative ideas. Even with this further increase, the total funding (on the order of $20 million) would not exceed the 4 percent recommendation of the HEPAP Subpanel on Accelerator Research and Development.

On a longer time scale, we should expect a proposal for a demonstration linear collider in the 100 GeV range. It must be emphasized that we do not, at this time, know that the required technology will exist. Even if identified, this technology will be new and interesting, but very uncertain. Such a demonstration machine, though of great importance to the future of the field, cannot be regarded as a facility for the high energy physics community and in no way alters the need and importance of the SSC.

VII. International Collaboration

High energy physics is truly an international scientific enterprise, with a long history of the exchange of ideas, people, and equipment. In addition to informal agreements, for example, between groups in the United States and in Western Europe, cooperative agreements between countries have been formalized to expedite exchanges. Examples of formal bilateral agreements involving the United States include agreements with the Soviet Union, with Japan, and with the People's Republic of China. Over the past 30 years, Western Europe has been enormously successful in consolidating the efforts of European particle physicists at CERN, whose facilities in Geneva, Switzerland, are now utilized by about 2,500 researchers from 13 Member States plus about 500 other physicists from non-Member States.

The level of international collaboration is actually much greater than indicated by formal agreements, and practice on large experiments today pools the talent and resources from several countries, whether or not they fall under formal bilateral agreements. There are over 60 foreign institutions involved in approved experiments in Fermilab's Tevatron II fixed-target program. Presently, there appear to be between 200 and 300 U.S. physicists involved in experiments abroad and more than 400 foreign scientists participating in experiments at U.S. laboratories. The available data suggests, moreover, that there is approximate parity in the exchange of capital equipment between the U.S. and other countries.

HEPAP reiterates its support for an open policy. It is the accepted practice at major accelerator laboratories throughout the world to accept proposals from any group, domestic or foreign. Approval and support have been and should continue to be judged on the basis of scientific merit and available resources through the usual peer review processes. DOE and NSF should continue to support U.S. participation in foreign programs whenever justified by the physics objectives and opportunities.

As detectors grow larger and the world's accelerator facilities become more individually unique in their capabilities, these exchanges of researchers become increasingly important in order to provide a full scope of opportunities for U.S. and foreign experimenters. Improved contractual or international agreements are necessary to facilitate the exchanges of personnel and equipment. These could, for example, expedite visa and customs formalities.

Other opportunities will arise in the future for collaboration in accelerator construction, for example, the mode established by DESY with HERA. We endorse securing international participation in all phases of the SSC project, commensurate with the goals of the U.S. High Energy Physics Program. Another area ripe for increased collaboration is the anticipated expansion of advanced accelerator research and development on new technologies for particle acceleration in the post-SSC era.

We note the inclusion of high energy physics in the Summit process and appreciate the efforts of the heads of state of the participating countries to facilitate international cooperation and to remove administrative obstacles to effective collaboration in science and technology.

VIII. Conclusions and Recommendations

The conclusions and recommendations of the 1985 summer study are best given by quoting the final section of the report of the study as is done below.

Conclusions

The physics justification for a multi-TeV high-luminosity hadron-hadron collider is even stronger today than it was in 1983 at the time of the original HEPAP recommendation. The technical successes achieved by the SSC R&D program in the intervening two years reinforce confidence that this facility can be built within the costs and on the time scale estimated in the Reference Designs Study.

We strongly reaffirm the SSC as the highest priority in the U.S. High Energy Physics program. A project of the magnitude of the SSC will clearly cause major redirection of resources during the next 10 years. However, there is no alternative to such a project for reaching the scientific objectives which are essential for the progress of the field. Further, we believe that it is possible to achieve a reasonable transition into the SSC program. Some of the existing programs will be terminating just as extensive experimental effort on SSC detectors will need to commence. The timely completion of the SSC will provide a truly forefront facility for the world's high energy physics community. We must point out, however, the inevitable deterioration of the U.S. program and the difficulty of maintaining continuity of the field if the SSC were delayed appreciably beyond the presently anticipated time scale. If this were the case, there would be no frontier facility in high energy physics in the U.S. in the mid-1990's.

We have evaluated the physics opportunities in the program for the next ten years of approximately 10 years before the SSC would come into operation. These opportunities provide for a rich physics program with excellent prospects for fundamental advances. The superconducting Tevatron II at Fermilab has recently come into operation at an energy of 800 GeV, the highest energy fixed-target facility in the world. The Fermilab Tevatron I Collider will become operational in 1987 and will be the world's highest energy hadron collider extending the energy range from 0.6 TeV now (at the CERN $S\bar{p}pS$) to 1.8 TeV. The SLC, which will come into operation in 1987 at the Stanford Linear Accelerator Center, will be the first e^+e^- collider to reach the energy of the Z^0 and also represents a pioneering effort toward a new class of electron-positron colliders.

These opportunities also include important programs at new facilities abroad. The CERN project, LEP, will become operational for physics in 1989 and will provide e^+e^- collisions initially in the Z^0 range and later at higher energies up to 100 GeV per beam. The TRISTAN project in Japan will become operational for physics in 1987 providing e^+e^- collisions up to a total energy of about 60 GeV. There will be major U.S. participation in research at both of these projects. The HERA project at DESY will become operational in 1990 with $e^\pm p$ collisions up to a center-of-mass energy above 300 GeV, opening new opportunities for research.

The Panel has identified a limited number of programs which, because of their intrinsic importance, their likely impact on the course of future research, and their key role in the U.S. program, should proceed with priority. The Panel places in this category: The CDF and D0 projects at Tevatron I, the L3 project at LEP, the Mark II and SLD projects at SLC, the CESR program, studies of CP violation with kaons, high sensitivity studies of rare kaon decays, and certain parts of the non-accelerator program as enumerated in Section III.E to be in this category. However, to realize the opportunities which will be available in the next ten years and to utilize properly the facilities which will exist, adequate support must be provided to the full physics research program. This is a broadly-based forefront program providing essential diversity and scope.

Finally, we note the importance of maintaining and strengthening the technology research in advanced accelerator R&D. This research, as noted in Section V., is essential to the long term progress of the field.

Recommendations

1. We recommend that the SSC R&D be given highest priority in the U.S. High Energy Physics Program so that the project can proceed to an early construction start and rapid completion. In particular, for FY 1986, we support the requested incremental allocation of $7 million to SSC R&D, primarily so that early substantial industrial involvement in the Magnet R&D effort can be initiated.

2. We recommend that the limited category of forefront programs identified in the report proceed with priority.

3. We recommend that the overall funding be adequate to permit the effective implementation of the broadly-based program providing essential diversity and scope with high priority to the special programs, and to pursue the crucial SSC R&D effort.

   Comment: For FY 1987 this would require a small increase beyond the FY 1985 total level of effort. With reduced construction activity, this would allow the increased funding required for the utilization of the new capabilities coming into operation (the SLC at SLAC and the Tevatron at Fermilab) and for the SSC R&D effort.

   It is clear that construction of SSC and fabrication of detectors for SSC will require incremental funding above this level. A funding profile such as shown in Section IV would ensure the scientific vitality and stature of the U.S. High Energy Physics Program during the period prior to SSC operation. After the SSC is

completed, it appears that an excellent program, including the SSC and a reduced non-SSC program, could be supported at a funding level about 10 percent above the current (FY 1985) level of effort.

4. **We recommend that advanced accelerator R&D be strongly supported. A continued and strengthened effort in this area is essential to the long term progress of the field.**

DISCUSSION

Mr. Fuqua. Thank you very much.

In the course of your work with the HEPAP committee, does the standard model make a number of predictions that can be verified by ongoing or planned experiments on current accelerators?

Dr. Sandweiss. Yes, it does. And indeed many of these results have been borne out. And it's that agreement which gives us the confidence in that model and it is that model, so to speak, sets the 1 TeV mass scale.

Mr. Fuqua. Well, what if you found out that the standard model was flawed?

Dr. Sandweiss. Well, that would be very interesting. That would be the first clue as to the structure that was behind the standard model. I mean, nobody believes that the standard model so to speak can possibly be the final theory. It has clear aspects that indicate it to be only a stepping stone, a theory which is partial. And so, we hope to find places where it doesn't work, and those places will be the clues for the next layer.

Mr. Fuqua. So you think it's still important to do the experiments—to build the SSC then?

Dr. Sandweiss. Oh, absolutely yes. I think the standard model is now sufficiently well established that there really can't be any doubt that this range is a very interesting range. And to some extent maybe I could answer one of the questions that was asked previously; what is the energy that we need?

Of course we don't know exactly what's going to happen. That's the nature of research. But there's no question either that as one extends the energy range, one will see more of the structure, one will see more of the pattern which is there. And that is one of the reasons for trying to pick the energy of the SSC as we have. To pick an energy which will give us the biggest view into that world.

It's a little bit like light microscopes. I mean, with the fairly bad microscope Mr. Van Leeuwenhock was able to find the microbes in his teeth, but he might not have done so well on viruses. So there's a whole spectrum, and undoubtedly that continues.

Mr. Fuqua. You've given a funding scenario for 1987, which assumes a real increase in total U.S. high energy physics program of about 8 percent from the 1985 level. What would be the increase above the 1986 level?

Dr. Sandweiss. I think the 1986—I'm not exactly sure. It would be larger because the 1986 level was lower in total than the 1985 level, yes.

Mr. Fuqua. You don't have a——

Dr. Sandweiss. I don't have it at hand, no. It would just be whatever the decrement added to that would be.

Mr. Fuqua. Mr. Barton?

Mr. Barton. Thank you, Mr. Chairman. I'd like to go back to your funding required for the high energy physics program on page 11 of your testimony, and there's a chart on page 14. You asked the question in your viewgraph but you didn't really answer it.

I'm a proponent of the Gramm-Rudman deficit reduction proposal which would require us to reach a zero deficit by fiscal year 1991. If that's passed, we're not going to be able to have guns and butter, so to speak, in the high energy physics program. We'll either, I think, have to make a decision to fund current projects or cut them back drastically and fund the SSC.

Given that scenario, which way would you go?

Dr. **Sandweiss**. Well, it's really a matter of detail. That is, there is no question that is worth sacrificing for the SSC. On the other hand, the time period of the SSC, even under the most favorable circumstance, is too long to approach by holding our breath. That is, if we really crippled the existing program we would lose several generations of graduate students, several generations of young faculty. You could in fact, by sufficient reduction, really cripple the field for a long time. And, of course, that wouldn't be intelligent. Then it would be better to stretch out the SSC.

So, it's really a question of detail. And we certainly didn't plan—we didn't claim to look at all possible scenarios. We just gave a typical one, and indeed admittedly a favorable one.

Mr. **Barton**. Well, you know, in fiscal year 1991 you show an SSC of $900 million, or the Department of Energy I should say, and the the non-SSC Program of $500 million. That totals $1.4 billion, which is over double what we're currently spending. And I don't believe—I mean, I wouldn't vote for that spending level, and I can't speak for the rest of the committee.

However, one question. On fiscal year 1987 you show an R&D budget for the SSC Program of $65 million. It's my understanding that the magnet design which was not chosen, the R&D on that for the next year would have been $5 million, and the design that was chosen, the R&D is somewhere in the neighborhood of $50 million.

If you had some budget restrictions, would you be one that would want to revisit the magnet design selection process?

Dr. **Sandweiss**. I personally wouldn't, but of course it's much better to ask Mr. Tigner and his colleagues.

Mr. **Barton**. Thank you, Mr. Chairman.

Mr. **Fuqua**. Mr. Stallings.

Mr. **Stallings**. Thank you, Mr. Chairman. Professor, what has been the modification and expansion history of accelerators in Europe, Japan, and the United States?

Dr. **Sandweiss**. I'm sorry, could you clarify that?

Mr. **Stallings**. Yes. Have we had any luck in modifying or expanding existing accelerators that are——

Dr. **Sandweiss**. Well, in a sense, yes. For example, the Fermilab Tevatron I and II Program builds on the accelerator which is there. The first stage in the Tevatron accelerates particles to about 150 GeV in the old Tevatron accelerator's so-called main ring, and that injects then into the superconducting ring which carries them up the rest of the way, 800 or 900, ultimately to 1 TeV. So that's one example.

The Stanford linear collider modification is another example in which the Stanford linac is the injector into the two collider arcs, although the linac had to be substantially upgraded to be able to do that. So that's a second example. And there may well be others, and I'm sure there are others, but maybe that's enough.

Mr. **Stallings**. Can the SSC be added onto an existing accelerator, or can we come to this same stage by modifying something that's already in existence?

Dr. **Sandweiss.** It would be best to ask this question to Mr. Tigner, who could give you a more accelerator expert answer. But certainly one part of the SSC is an injector of roughly 1 TeV. Fermilab is a machine with an injector—which could be an injector at 1 TeV. So clearly that part of it, except possibly for technical reasons perhaps it wouldn't work, I don't know, but possibly yes. But that needs really an expert decision, but it's certainly possible.

Mr. **Stallings.** Are there some basic problems with that though?

Dr. **Sandweiss.** There could be, but I don't know—it would have to be analyzed carefully. I would personally guess that from a technical point of view you could do that. Now, whether that would still be the best way to proceed, you'd have to balance the totality of that program against the totality of the different design.

Mr. **Stallings.** Is expansion being considered in the—as part of the requirements for the site for the SSC? I mean, are we looking at ways that we can continue to expand and change this SSC once we've built it? Is that part of the site selection process?

Dr. **Sandweiss.** I don't think it's a major part in the sense—if you're thinking of an expansion in terms of large energy upgrade, or several reasons—and again, I think the later witnesses will be able to give a more expert opinion—but one of the things is that he timing for the SSC is certainly of the order of 10 years no natter how optimistic one is, and it would have to operate for a while. So any upgrade would be something we would be looking at no sooner than say 15 years or so from now.

And by that time, we don't know really which way the physics vants to go. Maybe it wants a much bigger step, maybe it wants a tep in a different direction. Maybe, in fact, there are problems which make the upgrade more difficult by just putting magnets in he same tunnel. So it's very hard to look into the future and give high weight to this hypothetical decision that would not be taken ntil 15 years from now. And many of the ingredients of that deci-ion are really not available now.

So I think that largely the prevailing point of view—and it's not he only point of view—but the prevailing point of view is that that actor of the decision shouldn't be a very large part of it. For exam-le, one should not make a machine that's 20 percent more expen-ive in order to have this possibility at a later time.

Mr. **Stallings.** Thank you.

Mr. **Fuqua.** Mr. Fawell.

Mr. **Fawell.** Thank you, Mr. Chairman. This might be a difficult uestion, and I don't mean to be putting anybody on the spot, but ertainly you are a solid believer in the SSC. And I imagine most f the scientific community is, and I, as a layman, would say that I m, too. And we've got all kinds of potential problems that can ome along.

But are we, in your opinion, since this concept has been ad-anced, are you satisfied with the progress of moving ahead to cul-inate this project so indeed we will have this kind of a facility pable of being used within this decade or in the next 15 years? re we moving ahead as we ought to do?

Dr. **Sandweiss.** Well, I would say of course one would always—it ould be nice to have more support. But I think, in fact, the ogress which has been made, and I think Mr. Tigner will speak to that in more detail, is really very good. There has been a remarkable cooperative activity on this SSC R&D that's been spread out to the entire country, and indeed has benefited from the exchanges abroad as well. And, in fact, the technical answers, the time scale for the magnet selection was met. It was a time scale that was set up a year or a year and a half ago and it was met within a month of the time.

And yes, I think the answers to the questions, the R&D questions are coming. Not that we couldn't benefit and the ultimate machine might come faster if we could have a bit more, but up until now I think the progress hasn't been hurt very much. It may be that the more crucial moments are ahead of us.

Mr. Fawell. What about it being a cooperative venture rather than a U.S. venture?

Dr. Sandweiss. Well, I think in terms of its utilization there's no question that it will be a cooperative venture.

Mr. Fawell. Yes.

Dr. Sandweiss. And in terms—even I don't know how in the end it might be organized to be constructed. I think it is important for the United States to have on its site and to be a major supporter of a forefront facility in high energy physics. One of the things that worries us about the field is that if we look into the mid-1990's and we see accelerators that were upgraded in the mid-1980's, and some accelerators that will be 35 years old in the mid-1990's, we are concerned about the status and the position of the United States in the sense of its ability to have a vital program if it doesn't have forefront facilities of some kind on its own soil.

Mr. Fawell. Thank you.

Mr. Faqua. Mr. Mineta.

Mr. Mineta. No questions.

Mr. Fuqua. Mr. Bruce.

Mr. Bruce. No questions, Mr. Chairman.

Mr. Fuqua. Thank you very much.

Mr. Barton. Mr. Chairman, I have one more question.

Mr. Fuqua. All right.

Mr. Barton. You mentioned the international aspect and the number of international scientists.

Dr. Sandweiss. Right.

Mr. Barton. Are those international scientists all free world sci entists, or are some of them from Communist countries?

Dr. Sandweiss. Some of them are from Communist countries The number is rather small, but—I don't know the exact number but it's not more than 15 or 20 percent I would guess. Now, that's rough number and I could find the exact number for you.

Mr. Barton. Another question just on that same line. I'm tol that if we build the SSC, that it has a potential for defense-relate work with regards to the strategic defense initiative. If that is tru what methods or what procedures would be used, if any, to ensur that such data doesn't fall into the hands of the scientists that ar not from the free world?

Dr. Sandweiss. Well, my understanding of the origin of the stat ment you made is that some of the fundamental technologies an the fundamental scientific aspects that underlie anything like

SDI would also underlie some of the problems that we have to face in the SSC.

But I think it's the general feeling that the level of that work is at so basic a level that in fact it's very likely that it would be in fact unclassified work. And it isn't that some particular thing is going to be discovered per se. It would be a building up of a broad base of physics. And, of course, a building up of the expertise to build the things, which is in place where it's built up.

Mr. **Barton**. Thank you.

Mr. **Fuqua**. Thank you, and thank you very much, Professor Sandweiss.

[Questions and answers for the record follow:]

January 20, 1986

Responses to the Questions from the Subcommittee on Energy Development and Applications

by Jack Sandweiss

1. You state on page 1 of your testimony that "no significant deviations from the Standard Model have been found." What predictions, other than the absence of proton decay, does the Standard Model make that have been experimentally proven wrong?

   To date, there are no definite predictions of the standard model which have been proven wrong. The problem with the standard model is that it requires a large number of experimental parameters as input and that it does not address certain basic questions in fundamental physics. The standard model must be an incomplete theory albeit a very successful one within its range of application.

   The predictions of proton decay were made by theories which went beyond the standard model. Had they proved correct, they would have pointed the way to correct extension of the standard model.

2. Does the Standard Model make a number of predictions which can be verified by on-going or planned experiments on current accelerators, and if so, why is it not just as important to do these experiments as to build the SSC?

   Yes, the standard model does make many predictions which can be tested by on-going and planned experiments on current accelerators or on accelerators which are now under construction. It is indeed important to do these experiments as they will establish the full range of applicability of the standard model and provide important clues as to its correct extension.

   However, without the SSC we will not be able to explore the range of forces and physics which comprise the "deeper layer" beyond the standard model. Important clues -- yes, but a real exploration -- no, without the SSC. The situation is analogous to the study of nuclear physics before the development of accelerators. Atomic and molecular effects told quite a bit about the nucleus -- for example that there was a nucleus, its gross properties such as charge mass, etc. However, the study of the rich phenomena of nuclear physics -- artificial radioactivity, nuclear fusion and chain reactions, etc. could only be explored with the frontier accelerators of that period.

3. Consider a different funding scenario. Suppose that instead of about a 10% real increase to the total U.S. high energy physics program, which includes both the NSF and DOE, there is a level current dollar funding for the program. How would your priorities change? AND,

4. Suppose that incremental funding is not available and that the only way $65 million in SSC R&D could be obtained in FY 2987 would be by shifting funds from the "forefront programs" you have identified. How acceptable would such a reallocation of funds be to the U.S. high energy physics community?

The transfer of $65 million for SSC R and D in FY 87, from funds for current operations in high energy physics would, in my opinion, be contrary to the best interests of U.S. high energy physics.

The negative effects of so large a decrease would outweigh the benefits, important as they are, in proceeding rapidly with the SSC. In such a situation, the best course would be to transfer a smaller amount to the SSC R&D. I cannot at this point make a good estimate of how much that would be. A careful analysis the the (then) current status of the SSC R&D and of the on-going program would need to be carried out and the best compromise determined.

It is clear that the new facilities, the SCL and the Tevatron collider must be operated with adequately strong programs. It is also clear that the SSC R&D should proceed at a somewhat increased level relative to FY 86 if that effort is to remain viable for an SSC reality in the mid nineties.

There is no doubt that the high energy physics community sees the SSC as essential to the future of U.S. high energy physics and would be willing to make substantial sacrifices in on-going programs to further the reality of the SSC. It is necessary, however, to be concerned about cuts in the on-going programs which threaten the continued viability of the field and it is the best balance between these factors which will determine the compromise.

PANEL 2: SSC MAGNET SELECTION

Mr. **Fuqua**. Our next group of witnesses will discuss the SSC magnet selection which took place last month. And if they will come join at the table; Dr. Peter McIntyre, associate professor of physics at Texas A&M University, a scientific spokesman for the Texas Accelerator Center. He'll be accompanied by Dr. Russell Huson, manager of the center.

We also have Dr. Frank Sciulli, professor of physics at Columbia University, who served as chairman of the SSC Magnet Selection Advisory Panel. And other members of that panel with us today include Dr. John Hulm, director of corporate research at the Westinghouse R&D Center, who will also be accompanied by Dr. C.H. Dustmann, group leader for marketing and development of superconducting magnets for the BBC-Brown Group; and Mr. Parke Rohrer, consultant, who will be accompanied by Mr. Keith Bull, project leader for the underground facilities.

The remainder can come because we're going to take your statements together, and then we'll have questions at the end. Dr. McIntyre, we'll begin with you at this crowded table.

STATEMENT OF DR. PETER M. McINTYRE, SCIENTIFIC SPOKESMAN, TEXAS ACCELERATOR CENTER, THE WOODLANDS, TX, AND ASSOCIATE PROFESSOR OF PHYSICS, TEXAS A&M UNIVERSITY, COLLEGE STATION, TX; ACCOMPANIED BY DR. F. RUSSELL HUSON, MANAGER, TEXAS ACCELERATOR CENTER, THE WOODLANDS, TX

Dr. **McIntyre**. Thank you, sir. Mr. Chairman and members of the subcommittee, my name is Peter M. McIntyre. I'm the scientific spokesman for the Texas Accelerator Center. I'm very pleased and honored to be invited to appear at our committee today. I'd like to introduce to you Dr. Russell Huson, who's the director of the Texas Accelerator Center. We'll present the views of TAC on the status and the technical design of the superconducting supercollider, and on the importance of the SSC to the U.S. research program in high energy physics.

Well, I'd like to begin by telling a couple of things about the Texas Accelerator Center because unlike most of my colleague institutions here, we're the new fellas in town.

Mr. **Fuqua**. I'll tell you what, Dr. McIntyre, right at this point we've got a vote on the floor. So that we won't have to interrupt you during the middle of your statement we will take a short break while we run and vote, and we'll be right back.

Dr. **McIntyre**. At your pleasure.

[Whereupon, a brief recess was taken.]

Mr. **Fuqua**. Dr. McIntyre, we will try again one more time.

Dr. **McIntyre**. Thank you, sir. I'd like to first tell you about the Texas Accelerator Center. TAC is a new laboratory in the United States for accelerator research. It was created in March of 1984 as a collaboration among a number of universities and labs. Its mission is to establish a university-based laboratory for advanced accelerator research, to develop new technology for future accelerators, and to train students in accelerator physics and engineering.

TAC is the culmination of a growing commitment in Texas to high energy physics and accelerator research. As recently as 5 years ago, only one university in the State was engaged in high energy physics research. Today, five of our universities are involved in major high energy experiments at laboratories all over the world. And four of these—Rice University, the University of Houston, Texas A&M University, and the University of Texas—founded the Texas Accelerator Center.

TAC has received major funding support from the State of Texas, from our universities, and from private industry in the region, as well as DOE. TAC is operated by the Houston Area Research Center, a regional university/industry/government consortium for high technology research. It presently has a total staff of about 50 people, plus a number of short- and medium-term visitors from participating institutions, and 20 students in engineering and physics.

This latter represents about one-third of all students in accelerator research in the United States. And that is particularly relevant, we believe, today when there is a major demand for young people to go into this expanding field.

TAC's research facilities now include magnet fabrication shops, iquid helium refrigerators, high current power supplies, and a tate of the art computer network. During our first year and a half f life, TAC has developed the superferric design for the SSC. We've designed, built, and successfully tested 14 superferric magnets to date.

Our R&D program has been on schedule, on budget, and all of ur major R&D objectives have been achieved. General Dynamics Corp. is delivering the first 100-foot-long superferric magnet to TAC today. It is the longest magnet ever made by man. Construcion was on schedule and on budget. All preliminary tests have een very successful. In reviews of our work by the Department of Energy, the central design group, and industrial design groups, TAC has repeatedly been praised for the high standards of our work, the pace of results, and the cost effectiveness of our opertion.

In addition to work on the SSC, TAC is conducting research on ew acceleration mechanisms, including laser acceleration and nac collider R&D.

I'd like now to address some comments on the status of the techical design of the SSC and the magnet decision process. The techical design of the SSC has been the subject of an intense effort at ree national laboratories; Fermilab, Brookhaven, and Lawrence erkeley Lab, as well as TAC during the past year and a half. The esult of this effort was the development and evaluation of two degns for the superconducting magnets that are the technological eart of the SSC.

The two designs are a high field strength, 6 tesla, magnet, and a uperferric design, 3 tesla. The R&D effort has demonstrated cleary that the SSC could be built with either of the candidate designs, nd could be expected to perform to specification. This result reprents a major success for the development of the SSC.

The two designs are both viable and attractive candidates for the SC. This conclusion is borne out in the reports of central design group task forces on accelerator performance, magnet technology, operation and commissioning, and total cost.

In September of 1985, the central design group decided to adopt the high field-design for their preparation of an SSC construction proposal. The design decision is an important milestone for the SSC. TAC has already undertaken a strong role in the ongoing SSC effort under CDG leadership. TAC will perform several major R&D tasks in developing the chosen high field design and in preparing a construction proposal.

These tasks include the design of the correction magnets that will be used to steer and correct beam motion in the SSC, the quench protection system used to protect the magnets from damage in the event of a quench, and supercomputer studies of beam behavior in the SSC.

We would characterize the design choice that has been made as a judgment call between two attractive designs. A choice must be made. TAC does not agree with the CDG magnet decision. The technical considerations that lead to this disagreement have been communicated to DOE. It's particularly unfortunate in our view that the future upgrade capability was not considered relevant during the decision process.

What is important, however, is that a decision has been made. The chosen design is technically sound, and TAC is taking a major role in carrying it to success. We will bring the same enthusiasm and dedication to these new tasks as we have done in our work to date.

I'd like lastly to address briefly the importance, in our view, of the SSC for the United States and for the world. The superconducting supercollider is an important opportunity for the United States to resume leadership at the cutting edge of modern science. It will give us the means to probe the most fundamental building blocks of nature, the quarks and leptons, which Dr. Rubbia has eloquently told you about a few moments ago.

We have today a beautiful, but in some ways puzzling picture of nature. Almost all the matter of our universe is locked in in the protons and neutrons of the atomic nucleus. We now know that each of these contains three quarks located together by the strong force. The quarks themselves weigh only a small part of the mass of the proton, however. Almost all its mass, hence almost all the mass of the universe, is locked in the field energy of this strong force.

The SSC will be the essential tool with which we can probe the bonds of that force, and seek to better understand the substance of substance. In this quest, we are training the best and brightest of our young scientists in the richest creative tradition.

Along the way we're developing practical technologies that are of great value to our society. TAC, in particular, is working with industries to apply state-of-the-art accelerator technology to a number of real world problems. I'll cite a few of these.

First, ion beams can be used to improve the abrasion resistance of metal surfaces by a factor of 10. This can lead to better ball bearings and razor blades. Second, superferric magnets, of the kind we have designed for the SSC, can be adapted to make a rather ideal choice for compact, low-cost synchrotron light sources for microcircuit lithography. We are working to develop just such a design, and it can lead to better microchips and computers.

Third, TAC is working with the Texas Medical Center to develop a design for a superferric medical NMR magnet, which would increase the field and reduce the cost of present systems. This would lead to better and higher resolution, nonintrusive medical diagnosis.

Fourth, civil engineers at our universities have invented a new tunnel technology that promises a significantly increased tunneling rates and reduced tunneling costs for long tunneling projects. This promises savings for the SSC, and if successful, in addition to that and perhaps in disproportionate measure would save on the construction of sewers and subways that our cities so desperately need.

We believe that the combination of our work on developing the SSC for the next generation of fundamental research, and the application of its technology to practical needs represents the best synthesis of science in our modern world.

Thank you.

[The prepared statement of Dr. McIntyre follows:]

STATEMENT OF

PETER M. MCINTYRE

TEXAS A&M UNIVERSITY

BEFORE THE

SUBCOMMITTEE ON ENERGY AND DEVELOPMENT AND APPLICATIONS

OF THE

SCIENCE AND TECHNOLOGY COMMITTEE

OF THE

UNITED STATES HOUSE OF REPRESENTATIVES

OCTOBER 29, 1985

ON BEHALF OF

TEXAS ACCELERATOR CENTER
2319 TIMBERLOCH PLACE
THE WOODLANDS, TX 77380
(713) 363-0121

MY NAME IS DR. PETER M. MCINTYRE. I AM THE SCIENTIFIC SPOKESMAN OF THE TEXAS ACCELERATOR CENTER. I AM PLEASED TO BE INVITED TO APPEAR BEFORE THE HOUSE COMMITTEE ON SCIENCE AND TECHNOLOGY TODAY. I WOULD LIKE TO INTRODUCE DR. F. RUSSELL HUSON, THE DIRECTOR OF THE TEXAS ACCELERATOR CENTER. WE WILL PRESENT THE VIEWS OF THE TEXAS ACCELERATOR CENTER (TAC) ON THE STATUS OF THE TECHNICAL DESIGN OF THE SUPERCONDUCTING SUPER COLLIDER (SSC) AND THE IMPORTANCE OF THE SSC TO THE U.S. RESEARCH PROGRAM IN HIGH ENERGY PHYSICS.

THE TEXAS ACCELERATOR CENTER

WE WOULD FIRST LIKE TO TELL YOU ABOUT THE TEXAS ACCELERATOR CENTER. TAC IS A NEW LABORATORY FOR ACCELERATOR PHYSICS. IT WAS CREATED IN MARCH 1984 AS A COLLABORATION AMONG A NUMBER OF UNIVERSITIES AND LABORATORIES. ITS MISSION IS TO ESTABLISH A UNIVERSITY-BASED LABORATORY FOR ADVANCED ACCELERATOR RESEARCH, TO DEVELOP NEW TECHNOLOGY FOR FUTURE ACCELERATORS, AND TO TRAIN STUDENTS IN ACCELERATOR PHYSICS AND ENGINEERING.

TAC IS THE CULMINATION OF A GROWING COMMITMENT IN TEXAS TO HIGH ENERGY PHYSICS AND ACCELERATOR RESEARCH. FIVE YEARS AGO ONLY ONE UNIVERSITY IN THE STATE WAS ENGAGED IN HIGH ENERGY PHYSICS EXPERIMENTS. TODAY FIVE OF OUR UNIVERSITIES ARE INVOLVED IN MAJOR HIGH ENERGY EXPERIMENTS AT LABORATORIES ALL OVER THE WORLD, AND FOUR OF THESE - RICE UNIVERSITY, THE UNIVERSITY OF HOUSTON, TEXAS A&M UNIVERSITY AND THE UNIVERSITY OF TEXAS - FOUNDED THE TEXAS ACCELERATOR CENTER.

TAC IS OPERATED BY THE HOUSTON AREA RESEARCH CENTER (HARC), A REGIONAL UNIVERSITY/INDUSTRY/GOVERNMENT CONSORTIUM FOR HIGH-TECHNOLOGY RESEARCH. TAC PRESENTLY HAS A TOTAL STAFF OF ABOUT 50, PLUS A NUMBER OF SHORT- AND MEDIUM-TERM VISITORS FROM PARTICIPATING INSTITUTIONS AND 20 STUDENTS IN

ENGINEERING AND PHYSICS. ITS RESEARCH FACILITIES NOW INCLUDE MAGNET FABRICATION SHOPS, LIQUID HELIUM REFRIGERATOR, HIGH-CURRENT POWER SUPPLIES, AND A STATE-OF-THE-ART COMPUTER NETWORK.

DURING ITS FIRST YEAR AND A HALF OF LIFE, TAC HAS DEVELOPED THE SUPERFERRIC DESIGN FOR THE SSC. WE HAVE DESIGNED, BUILT AND SUCCESSFULLY TESTED 14 SUPERFERRIC MAGNETS TO DATE. GENERAL DYNAMICS CORP. IS DELIVERING THE FIRST 100 FOOT LONG SUPERFERRIC MAGNET TO TAC TODAY. IT IS THE LONGEST MAGNET EVER MADE BY MAN. ALL PRELIMINARY TESTS HAVE BEEN VERY SUCCESSFUL. IN REVIEWS OF OUR WORK BY THE DEPARTMENT OF ENERGY, THE CENTRAL DESIGN GROUP, AND INDUSTRIAL DESIGN GROUPS, TAC HAS REPEATEDLY BEEN PRAISED FOR THE HIGH STANDARDS OF OUR WORK, THE PACE OF RESULTS, AND COST-EFFECTIVENESS OF OUR OPERATION.

STATUS OF THE TECHNICAL DESIGN OF THE SSC

THE TECHNICAL DESIGN OF THE SSC HAS BEEN THE SUBJECT OF AN INTENSE EFFORT AT THREE NATIONAL LABORATORIES (FERMILAB, BROOKHAVEN, AND LAWRENCE BERKELEY LAB) AND TAC DURING THE PAST YEAR AND A HALF. THE RESULT OF THIS EFFORT WAS THE DEVELOPMENT AND EVALUATION OF TWO DESIGNS FOR THE SUPERCONDUCTING MAGNETS THAT ARE THE TECHNOLOGICAL HEART OF THE SSC. THE TWO DESIGNS ARE A HIGH-FIELD-STRENGTH (6 TESLA) MAGNET AND A SUPERFERRIC DESIGN (3 TESLA). THE R&D EFFORT HAS DEMONSTRATED CLEARLY THAT THE SSC COULD BE BUILT WITH EITHER OF THE CANDIDATE DESIGNS, AND COULD BE EXPECTED TO PERFORM TO SPECIFICATION. THIS RESULT REPRESENTS A MAJOR SUCCESS FOR THE DEVELOPMENT OF THE SSC.

IN SEPTEMBER 1985, THE CENTRAL DESIGN GROUP DECIDED TO ADOPT THE HIGH-FIELD DESIGN FOR THEIR PREPARATION OF AN SSC CONSTRUCTION PROPOSAL. THE DESIGN DECISION IS AN IMPORTANT MILESTONE FOR THE SSC. TAC HAS ALREADY UNDERTAKEN A STRONG ROLE IN THE ONGOING SSC EFFORT UNDER CDG LEADERSHIP. TAC WILL PERFORM SEVERAL MAJOR R&D TASKS IN DEVELOPING THE CHOSEN HIGH-FIELD DESIGN AND IN PREPARING A CONSTRUCTION PROPOSAL. THESE TASKS INCLUDE: THE DESIGN OF THE CORRECTION MAGNETS THAT WILL BE USED TO STEER AND CORRECT BEAM MOTION IN THE SSC; THE QUENCH PROTECTION SYSTEM USED TO PROTECT THE MAGNETS FROM DAMAGE IN THE EVENT OF A QUENCH; AND SUPER-COMPUTER STUDIES OF BEAM BEHAVIOR IN THE SSC.

TAC DOES NOT AGREE WITH THE CDG MAGNET DESCISION. THE TECHNICAL CONSIDERATIONS THAT LEAD TO THIS DISAGREEMENT HAVE BEEN COMMUNICATED TO DOE. WHAT IS IMPORTANT HOWEVER IS THAT A DECISION HAS BEEN MADE, THE CHOSEN DESIGN IS TECHNICALLY SOUND, AND TAC IS TAKING A MAJOR ROLE IN CARRYING IT TO SUCCESS. WE WILL BRING THE SAME ENTHUSIASM AND DEDICATION TO THESE TASKS AS WE HAVE IN OUR WORK TO DATE.

THE IMPORTANCE OF THE SSC

THE SUPERCONDUCTING SUPER COLLIDER IS AN IMPORTANT OPPORTUNITY FOR THE .S. TO RESUME LEADERSHIP AT THE CUTTING EDGE OF MODERN SCIENCE. IT WILL IVE US THE MEANS TO PROBE THE MOST FUNDAMENTAL BUILDING BLOCKS OF NATURE - HE QUARKS AND LEPTONS. WE HAVE TODAY A BEAUTIFUL BUT IN SOME WAYS UZZLING PICTURE OF NATURE. ALMOST ALL THE MATTER OF OUR UNIVERSE IS OCKED IN THE PROTONS AND NEUTRONS OF THE ATOMIC NUCLEUS. WE NOW KNOW THAT ACH OF THESE CONTAINS THREE QUARKS, LOCATED TOGETHER BY THE STRONG FORCE. E QUARKS THEMSELVES WEIGH ONLY A VERY SMALL PART OF THE MASS OF THE OTON, HOWEVER, ALMOST ALL ITS MASS, HENCE ALMOST ALL THE MASS OF THE

UNIVERSE, IS LOCKED IN THE FIELD ENERGY OF THE STRONG FORCE! THE SSC WIL
BE THE ESSENTIAL TOOL WITH WHICH WE CAN PROBE THE BONDS OF THE STRON
FORCE, AND SEEK TO BETTER UNDERSTAND THE SUBSTANCE OF SUBSTANCE. IN THIS
QUEST WE ARE TRAINING THE BEST AND BRIGHTEST OF OUR YOUNG SCIENTISTS IN TH
RICHEST CREATIVE TRADITION.

ALONG THE WAY WE ARE DEVELOPING PRACTICAL TECHNOLOGIES THAT ARE O
GREAT VALUE TO OUR SOCIETY. TAC IS WORKING WITH INDUSTRIES TO APP
STATE-OF-THE-ART ACCELERATOR TECHNOLOGY TO A NUMBER OF REAL-WORLD PROBLEM

1) ION BEAMS CAN IMPROVE THE ABRASION RESISTANCE OF METAL SURFACES
A FACTOR OF TEN - BETTER BALL BEARINGS AND RAZOR BLADES;
2) SUPERFERRIC MAGNETS APPEAR TO BE AN IDEAL CHOICE FOR COMPAC
LOW-COST SYNCHROTON LIGHT SOURCES FOR MICROCIRCUIT LITHOGRAPHY - BET
MICROCHIPS AND COMPUTERS;
3) TAC AND THE TEXAS MEDICAL CENTER ARE DEVELOPING A SUPERFER
MEDICAL NMR MAGNET TO INCREASE THE FIELD AND REDUCE THE COST OF PRES
SYSTEMS - BETTER NONINTRUSTIVE MEDICAL DIAGNOSIS.
4) CIVIL ENGINEERS AT OUR UNIVERSITIES HAVE INVENTED A NEW TUN
TECHNOLOGY THAT PROMISES TO SIGNIFICANTLY INCREASE TUNNELING RATES
REDUCE COSTS - BETTER AND CHEAPER SSC, SEWERS, AND SUBWAYS.

WE BELIEVE THAT THE COMBINATION OF OUR WORK ON DEVELOPING THE SSC
THE NEXT GENERATION OF FUNDAMENTAL RESEARCH AND THE APPLICATION OF
TECHNOLOGY TO PRACTICAL NEEDS REPRESENTS THE BEST SYNTHESIS OF SCIENCE
THE MODERN WORLD.

Mr. **Fuqua**. Thank you very much, Dr McIntyre.

Now we will hear from Dr. Sciulli.

[The biographical sketch of Dr. Sciulli follows:]

Biographical Sketch of Frank Sciulli

Birthdate: August 22, 1938

EDUCATION

A.B.: University of Pennsylvania—1960
M.S.: University of Pennsylvania—1961
Ph.D.: University of Pennsylvania—1965

POSITIONS

Research Fellow, Univ. of Pennsylvania—1965-66
Research Fellow, Caltech—1966-68
Assistant Professor, Caltech—1969-71
Associate Professor, Caltech—1971-77
Professor, Caltech—1977-80
Professor, Columbia University—1981-

RECENT SERVICE

High Energy Physics Advisory Panel (DOE), 1977-81
Physics Advisory Committee (Fermilab), 1981-84
HEPAP Woods Hole Subpanel, 1982
DOE Advisory Panel for Non-Accelerator Experiments, 1981-83
URA Visiting Committee at Fermilab, 1982; Chairman 83, 84
Tevatron Association of Fixed Target Spokesmen, Executive Committee, 1984-85
NSF Advisory Committee for Physics, 1984-
Associate Editor, Zeitschrift fur Physik, 1985-
Magnet Selection Advisory Panel for SSC, Chairman 1985

RESEARCH ACTIVITIES

Primarily in experiments on the Week Interactions of Elementary Particles.

For the past fifteen years, I have carried out a program of experiments dealing with the interactions of neutrinos with matter. Presently, I am beginning involvement with an experiment (ZEUS) to investigate electron-proton interactions with colliding beam energies at HERA.

STATEMENT OF DR. FRANK SCIULLI, CHAIRMAN, SSC MAGNET SELECTION ADVISORY PANEL; AND PROFESSOR OF PHYSICS, COLUMBIA UNIVERSITY, NEW YORK, NY

Dr. **Sciulli**. I have submitted with my written material a brief biographical sketch. Of relevance to my appearance here is my familiarity, through my own research with large experimental systems in the field of elementary particles, and my experience with advisory tasks of a similar nature. Over the past several years I've been asked to advise each of the various laboratories and the funding agencies on the approval and review of large technical projects.

My purpose today is to review for this subcommittee the process of magnet selection for the superconducting supercollider. I was asked by the director, last April, of the central design group to serve as the chairman of the Magnet Selection Advisory Panel to advise him on the selection of the most appropriate magnet element for the SSC. This formal selection process is unusual, reflecting the importance attached by the U.S. high energy physics community to securing the best and most cost-effective possible technology for the SSC design.

There were two basic and rather different design concepts advocated. The cosine theta magnet, which obtains the magnetic field solely through use of current carrying superconductor, is exemplified by the D design; the superferric magnet, on the other hand, obtains its magnetic field partly through the use of superconductor and partly through the placement of iron, and is exemplified by the C design. Since the D design achieves a magnetic field about twice as large as that of the C design, a given accelerator need only be half the circumference utilizing the D design. More detailed descriptions of these and the other candidate magnets, as well as recommendation of the panel, can be found in the panel's report, which is available to you.

The charge to the panel and the membership of the panel were chosen several months in advance of its meeting. These were specified by the director of the central design group in consultation with myself and with each of the four proponent R&D centers; Brookhaven National Laboratory, Fermi National Laboratory, Lawrence Berkeley Laboratory, and the Texas Accelerator Center. The proponents had direct impact on both the panel charge and on its membership.

The complete charge to the panel is included in the panel's report as appendix B. I quote here from this charge the criteria for selection to be used in the selection process.

> The criteria to be used in making an overall recommendation are: one, relative capital cost of an SSC facility employing a particular basic magnet design; two, workability of the basic designs presented; three, complexity of the overall magnet system inherent to the particular basic design; four, operational complexity of an SSC employing the particular basic design; five, relative flexibility of an SSC design employing the particular basic design; six, likely impact of the basic magnet design on the SSC construction schedule; seven, R&D time and effort needed to develop the basic design; eight, accelerator physics considerations; nine, other considerations deemed appropriate by the advisory panel.

The approximate relative weight applied in making the recommendation is in the order indicated in the charge with particular emphasis on the first four items. I emphasize that this was largely a technical decision based on technical information.

Clearly, to make such a recommendation requires individuals encompassing broad technical expertise in magnets, magnet systems, and construction of physical plant to house the accelerator. I believe that the membership of the panel reflected both breadth and depth in this regard.

The individuals constituting the panel, in addition to myself, were Dr. Eberhard Keil, from CERN, who is a well-known accelerator physicist with experience in the design and operation of larg accelerator systems, including the CERN ISR and LEP; Neil Lane from the University of Colorado, who is a theoretical physicis highly knowledgeable in science policy, and who was chairman o the Physics Department at Rice University. He was also Associat Director for Physics at the NSF when important decisions ther were being made on facilities, and is presently the chancellor a the University of Colorado.

Michael McAshan, a low temperature physicist at HEPL Lab, i highly experienced in the design and construction of large cryogenic systems. John Rees from Stanford University, was responsib for the construction, commissioning, and operation of the SLA

PEP facility, and is presently Associate Director of SLAC, responsible for construction of the Stanford linear collider facility.

Parke Rohrer, who is with us today, is an expert on conventional construction, was head of the DUSAF construction at Fermilab, and responsible for conventional construction for the CBA facility at Brookhaven.

Alvin Tollestrup, from the Fermi National Accelerator Laboratory, is an experimental physicist renowned as a problem solver for technical problems affecting accelerators, and was instrumental in resolving the technical difficulties of the early Saver/Tevatron magnet design.

And finally, Bjorn Wiik, from the University of Hamburg and DESY, is an experimental physicist with long experience at DESY accelerators, and presently is an Associate Director at DESY and has primary responsibility for the proton beam magnet systems of the HERA facility.

The consultants to the panel, two of whom are with us today, were Ray Beuligmann, vice president for research and engineering, General Dynamics Convair Division; Cord-Henrich Dustmann, group leader for marketing and development of superconducting magnets for Brown Boveri & Cie; and John Hulm, director of corpo-rate research, Westinghouse R&D Center.

In order to be well informed on the technical issues, the panel btained a large quantity of detailed information prior to the meetng, which is listed in my written submission and I won't bother eading. These included detailed information on the technical nagnet designs by the proponents, the report of a special task orces, including one on commissioning and operations, as well as ost comparisons compiled by the Central Design Group.

Furthermore, considerable additional technical material was vailable to the panel members prior to and during the meeting.

The panel, including consultants, formally met on the days beinning Sunday, August 25 until Thursday, August 29. I should say hat most of those days were 14-hour days. The detailed agenda of he meeting is included as appendix D of the report.

Briefly, the first day was primarily concerned with technical ssues having to do with the magnet designs, status of the R&D on hose designs by the principle advocates, and technical questions osed by the Panel to the proponents to be answered later.

The morning of the second day was devoted to issues involving he commissioning and operation of an accelerator built using each f the candidate magnets, and the cost of magnets and related osts, including tunneling, as summarized by the Central Design roup. Most of the afternoon of this day was spent in open discuson by participants and panel of all relevant issues.

The principal issue contested was the cost summary of the Cenal Design Group, as argued by the proponents from the Texas Acelerator Center. Ample opportunity was provided for relevant sues to be aired. A summary of the points of contention was proided by the Texas Accelerator Center and was included as appenx H of the panel's report.

The morning of the third day was spent in hearing responses by e proponents to technical questions posed by the panel. In my pinion, these 2½ days of testimony provided adequate time to explore all relevant issues. There were no requests to prolong testimony on any relevant issue beyong that time by any participant.

The remaining 2½ days were spent in deliberations by the panel in executive session and drafting of the report. I emphasize that the thrust of these deliberations was in response to the criteria described above. That is, these were technical issues discussed by a group of technical experts.

An outline of the principle judgments and recommendations by the panel follows; one, there is at present adequate information on which to base a technical decision about the magnet type; two, the high-field cosine theta, one beam per cryostat, that is, design D, was recommended unanimously by the panel. An alternate cosine theta version with two beams per cryostat, design B, was rejected due to the commissioning and operation complications.

Four, the promise of 2 years ago that the superferric design would provide a simpler, cheaper SSC has not come true. The complexity of the superferric magnet, design C, has increased with time. I should say that the reason one can make this judgment is due to very substantial work by the Texas Accelerator Center. If that work had not been done, we would not know or have enough information on which to base such a judgment.

Five, the total magnet related costs for the cosine theta and superferric designs, as presently conceived, are comparable. The Central Design Group costs comparisons indicate that the superferric system would be more expensive.

Six, the panel questioned the contingency costs used by the Central Design Group for the superferric design. These presumed that the magnet, as presently designed, would be constructed. In the panel's view, there is a real possibility that further R&D will indicate even higher total project costs than provided by the Central Design Group for the superferric design, exclusive of R&D costs.

Seven, the long R&D history and production experience on the cosine theta style was deemed adequate to provide a reliably predictable cost estimate for the D design. Eight, the commissioning and operations considerations indicate higher operating costs for a larger ring or a lower field magnet.

Nine, the industrial consultants stated in an appendix to our report that both styles were buildable by industry, but that there is a higher degree of cost and schedule uncertainty with the superferric style magnet. They agreed with the Panel that the cost contingency factor for the superferric style should be greater than stated.

It is perhaps worth noting several issues which affected these recommendations, and which were considered in depth by the committee. Firstly, the TAC group argued at the meeting that the appropriate maximum magnetic field should be presumed 6½ percent higher than previously assumed. Based on their own technical evaluation, the Panel did not agree with this argument.

B, that since these magnets are presumed to be constructed by industry, there were issues related to the readiness of each design for production and the reliability of the magnet cost estimates for production. Drs. Hulm and Dustmann are here today, and I believe Dr. Hulm's testimony will relate to these issues.

Lastly, the TAC group argued at the meeting that the tunneling costs used by the Central Design Group were too high. The Panel did not agree. Now, Mr. Parke Rohrer and Mr. Keith Bull are present today and there will be testimony on this issue. This is relevant because the fraction of total magnet related cost for tunneling is higher for the superferric C design than for the consume theta D design.

However, I should mention that so long as we discussed the ange of values of costs discussed to date on the tunneling issue, on he tunneling cost, this is not the crucial issue on which the deci-ion turns. Even with the lower costs advocated by the TAC group, he Central Design Group estimates show the superferric costs to e higher. Furthermore, this is without any added contingency for roducing the C magnet, judged necessary by the Panel.

In conclusion, just let me say that I believe that the decision by e Director of the Central Design Group on the magnet selection an important and correct one, and so that we can get on with the tailed work regard to make a complete design for the SSC.

Thank you.

[The prepared statement of Dr. Scuilli follows:]

Magnet Selection for the Supercollider

Frank Sciulli, Columbia University

Testimony before the Subcommittee on Energy Development
and Applications, Committee on Science and Technology,
U.S. House of Representatives

October 29, 1985

A brief biographical sketch is enclosed with my written submission. Of relevance to my appearance here is my familiarity, through my own research, with large experimental systems in the field of Elementary Particles and my experience with advisory tasks of a similar nature. Over the past several years, I have been asked to advise each of the various laboratories and the funding agencies on the approval and review of large technical projects.

My purpose today is to review for this Subcommittee the process of magnet selection for the Superconducting Super Collider. I was asked by the director of the Central Design Group (CDG) to serve as the chairman of a Magnet Selection Advisory Panel to advise him on the selection of the most appropriate magnet element for the SSC. This formal selection process is unusual, reflecting the importance attached by the U.S. High Energy Physics community to securing the best and most cost effective possible technology for the SSC design.

There were two basic, and rather different, design concepts advocated. The cosθ magnet, which obtains the magnetic field solely through use of current-carrying superconductor, is exemplified by the "D" design; the superferric magnet, which obtains the magnetic field partly through the use of superconductor and partly through the placement of iron, is exemplified by the "C" design. Since the D design achieves a magnetic field about twice as large as that of the C design, a given accelerator need only be half the circumference utilizing the D design. More detailed descriptions of these and other candidate magnets, as well as recommendation of the panel, can be found in the Panel's report, "SSC Magnet Selection Advisory Panel Report to the Director of the Central Design Group, September 9, 1985".

The charge to the Panel and the membership of the Panel were chosen several months in advance of its meeting. These were specified by the director of the Central Design Group in consultation with myself and with each of the four proponent R & D centers: Brookhaven National Laboratory (BNL), Fermi National Accelerator Laboratory (FNAL), Lawrence Berkeley Laboratory (LBL), and the Texas Accelerator Center (TAC). The proponents had direct impact on both the Panel charge and its membership.

The complete charge to the Panel is included in the Panel's report as Appendix B. I quote here from this charge the criteria for selection to be used in the selection process.

... "The Criteria to be used in making an overall recommendation are:

1. Relative capital cost of an SSC facility employing a particular Basic Magnet Design.
2. Workability of the Basic Designs presented.
3. Complexity of the overall magnet system inherent to the particular Basic Design.
4. Operational complexity of an SSC employing the particular Basic Design.
5. Relative flexibility of an SSC design employing the particular Basic Design.
6. Likely impact of the Basic Magnet Design on the SSC construction schedule.
7. R & D time and effort needed to develop the Basic Design.
8. Accelerator Physics considerations.
9. Other considerations deemed appropriate by the Advisory Panel."

The approximate relative weight applied in making the recommendation is in the order indicated in the charge, with particular emphasis on the first four items. I emphasize that this was largely a technical decision based on technical information.

Clearly, to make such a recommendation requires individuals encompassing broad technical expertise in magnets, magnet systems, and construction of physical plant to house the accelerator. I believe that the membership of the Panel reflected both breadth and depth in this regard. The individuals constituting the Panel are listed:

Frank Sciulli, chairman - Columbia University.

Eberhard Keil - CERN
Well-known accelerator physicist with experience in the design and operation of large accelerator systems, including the CERN ISR and LEP.

Neil F. Lane - Univ. of Colorado
Theoretical physicist highly knowledgeable in science policy. Chairman, Physics Dept., Rice Univ.; Assoc. Director for Physics at NSF; Chancellor at Univ. of Colorado.

Michael S. McAshan - Stanford Univ.
Low temperature physicist at HEPL Lab highly experienced in design and construction of large cryogenic systems.

John Rees - Stanford Univ.
Responsible for construction, commissioning, and operation of the SLAC PEP facility. Associate Director of SLAC, responsible for construction of the SLC facility.

Parke Rohrer - Rohrer Associates
Expert on conventional construction. Head of DUSAF construction at Fermilab; responsible for conventional construction for the CBA facility at Brookhaven.

Alvin Tollestrup - Fermi National Accelerator Laboratory
Experimental physicist renowned as a problem solver for technical problems affecting accelerators; instrumental in resolving the technical difficulties of the early SAVER/TEVATRON magnet design.

Bjorn Wiik - Univ. of Hamburg; DESY
Experimental physicist with long experience at DESY accelerators. Presently, as Associate Director at DESY, has primary responsibility for the proton beam magnet systems of HERA facility.

Consultants to the Panel:

Ray F. Beuligmann - Vice President for Research and Engineering, General Dynamics Convair Division.

Cord-Henrich Dustmann - Group Leader for Marketing and Development of Superconducting Magnets, Brown, Boveri, and Cie.

John K. Hulm - Director of Corporate Research, Westinghouse R & D Center.

In order to be well informed on the technical issues, the Panel obtained a large quantity of detailed information prior to the meeting, which is listed below and included as Appendix C of the Panel Report.

(mailed August 16, 1985)

1. Report of Cost Comparisons for SSC Magnet-Dependent Systems, SSC-SR-1012, (August 15, 1985).
2. SSC Aperture Estimate for Cost Comparisons, SSC-SR-1013, (August 9, 1985).
3. Recent Magnet Test Data and Information from BNL (August 2, 1985).
4. Recent Magnet Test Data and Information from FNAL (August 5, 1985).
5. Recent Magnet Test Data and Information from TAC (August 15, 1985).

(mailed August 5, 1985)

6. Report of Technical Magnet Review Panel, SSC-SR-1010 (July 25, 1985) (and cover letter of Chairman TMRP).
7. SSC Interim Report, SSC-SR-1011 (June 1985).
8. Vol. 1 Reference Designs Study Report (May 8, 1984).
9. Agenda for August 25 meeting.

(mailed July 8, 1985)

10. Report of Task Force on SSC Commissioning and Operations, SSC-SR-1005, (July 1, 1985).

These include detailed information on the technical magnet designs by the proponents, the report of a special task force on commissioning and operating, as well as the cost comparisons compiled by the Central Design Group. Furthermore, considerable additional technical material was available to the Panel members prior to and during the meeting.

The Panel, including Consultants, formally met on the days beginning Sunday, August 25 until Thursday, August 29. The detailed agenda of the meeting is included as Appendix D of the report. Briefly, the first day was primarily concerned with technical issues having to do with the magnet designs, status of the R & D on those designs by the principle advocates, and technical questions posed by the Panel to the proponents to be answered later. The morning of the second day was devoted to issues involving the commissioning and operation of an accelerator built using each of the candidate magnets and the cost of magnets and related costs (including tunneling) as summarized by the Central Design Group. Most of the afternoon of this day was spent in open discussion by participants and Panel of all relevant issues. The principal issue contested was the cost summary of the Central Design Group, as argued by the proponents from the Texas Accelerator Center. Ample opportunity was provided for relevant issues to be aired; a summary of the points of contention was provided by the TAC and was included as Appendix H of the report. The morning of the third day was spent in hearing responses by the proponents to technical questions posed by the Panel. In my opinion, these two and one-half days of testimony provided adequate time to explore all relevant issues. There were no requests to prolong testimony on any relevant issue beyond that time by any participant.

The remaining two and one-half days were spent in deliberations by the Panel in executive session and drafting of the report. I emphasize that the thrust of these deliberations was in response to the criteria described above. That is, these were technical issues discussed by a group of technical experts.

An outline of the principle judgments and recommendations made by the Panel follows:

(1) There is at present adequate information on which to base a technical decision about the magnet type.

(2) The high-field, cosθ, one beam per cryostat (design D) is recommended unanimously.

(3) A cosθ version with two beams per cryostat (deign B) is rejected due to commissioning and operating complication.

(4) The promise of two years ago that the superferric design would provide a simpler, cheaper SSC has not come true. The complexity of the superferric magnet (design C) has increased with time.

(5) The total magnet-related costs for the cosθ and superferric designs, as presently conceived, are comparable. The Central Design Group costs comparisons indicate that the superferric system would be more expensive.

(6) The Panel questioned the contingency costs used by the Central Design Group for the superferric design (C). These presumed that the magnet as presently designed would be constructed. In the Panel's view, there is a real possibility that further R & D will indicate even higher total project costs than provided by the CDG for the superferric design, exclusive of R & D costs.

(7) The long R & D history and production experience on the cosθ style was deemed adequate to provide a reliably predictable cost estimate for the D design.

(8) The Commissioning and Operations considerations indicate higher operating costs for a larger ring, or lower field magnet.

(9) The Industrial Consultants stated that both styles were buildable by industry, but that there is a higher degree of cost and schedule uncertainty with the superferric style magnet. They agreed with the Panel that the cost contingency factor for the superferric style should be greater than stated.

It is perhaps worth noting several issues which affected these recommendations, and which were considered in depth by the committee.

(a) The TAC group argued at the meeting that the appropriate maximum magnetic field should be presumed 6 1/2% higher than previously assumed. Based on their own technical evaluation, the Panel did not agree with this argument.

(b) Since these magnets are presumed to be constructed by industry, there were issues related to the readiness of each design for production and the reliability of the magnet cost estimates for production. Drs. R. Beuligmann, J. Hulm, and C.-H. Dustmann are present today. Dr. Beuligmann's testimony will relate to these issues.

(c) The TAC group argued at the meeting that the tunneling costs used by the Central Design Group were too high. The Panel did not agree. Mr. E. Parke Rohrer and Mr. Keith Bull are present today, and there will be testimony on this issue. This is relevant because the fraction of total magnet-related cost for tunneling is higher for the superferric C design than for the cosθ D design. However, I should mention that, so long as we discuss the range of values discussed to date on the tunneling costs, this is not the crucial issue on which the decision turns. Even with the lower tunnel costs advocated by the TAC group, the CDG estimates show the superferric total costs to be higher. Furthermore, this is without any added contingency for producing the C-magnet, judged necessary by the Panel.

Mr. **Fuqua**. Thank you very much.

[The biographical sketches of Dr. Hulm, Dr. Dustmann, and Dr. Beuligmann follow:]

Dr. John K. Hulm, Director of Corporate Research and R&D Planning, Westinghouse Research & Development Center

Dr. Hulm is responsible for planning and developing the R&D Center technical and scientific program, coordinating the technical activities of the Center with the goals of the Westinghouse groups, and obtaining corporate and other funding for the projects being conducted by the R&D Center Staff. He is responsible for R&D contract marketing and administration.

Dr. Hulm attended Cambridge University, England, where he received his B.S. and M.A. in mathematics and physics and his Ph.D. in physics (1949). He is also a graduate of the Advanced Management Program, Harvard Business School (1970). Dr. Hulm served as the Scientific Attache, U.S. Embassy London from 1974–1976. Dr. Hulm was a research fellow and professor at the University of Chicago from 1949 to 1954. He joined Westinghouse in 1954 and has held several management positions at the R&D Center, including director of cryogenics, director of solid state research, director of systems research, and manager, of the Chemistry Research Division. In 1980, he received the Westinghouse order of merit for his pioneering efforts in the application of superconductivity to electric power technology. Dr. Hulm has published over 100 technical papers relating to superconductivity ferroelectrics, magnetic materials, and semiconductors. He received the John Price Wetherill medal of the Franklin Institute (1964), the IBM international prize of materials research (American Physical Society 1980), and was elected to the U.S. National Academy of Engineering in 1980. He has served on many U.S. Government advisory panels. He is currently on the Advisory Boards of Brookhaven National Laboratory, the National Magnet Laboratory (MIT), the National Bureau of Standards, the Los Alamos National Laboratory, and the Board of Overseers, Universities Research Association.

Dr. Cord-Henrich Dustmann, Marketing and Development Super-Conducting Magnets, Power Generation Division, Brown, Boveri & CIE AG

Dr. Dustmann studied physics at the Free University of Berlin and the Technical University of Karlsruhe. From 1970–74 he worked on the development of the collective ION Accelerator at the Institute for Experimental Physics. The thesis was written on the development and testing of the high current pulsed electron gun needed for the electron ring accelerator.

1974–79 He was at the Institute of Technical Physics of the Nuclear Research Centre at Karlsruhe. After having developed and tested the flying capacitor system for energy transfer between superconducting coils he was in charge of TEHE TESPE experiments which is a small superconducting Torus dedicated to the development of superconducting coils for fusion.

1979—Today he is in charge of all activities on superconducting magnets at Brown Boveri and CIE AG in Mannheim. In this time BBC fabricated the first industry-developed accelerator magnets for the HERA project. Other magnets have been produced for a superconducting sector cyclotron, an electron resonance ION source and RHIC. Design and manufacturing studies have been worked out for SSC, Synchrotron High Source Magnetsystems, ore separation magnet systems and fusion magnet systems.

Raymond F. Beuligmann, Ph.D., Vice President, Research and Engineering, General Dynamics Convair Division

Education: University of Illinois, B.S.E.E., 1957, University of Illinois, M.S.E.E., 1958, University of Illinois, Ph.D.E.E., 1961.

Dr. Beuligmann joined the General Dynamics Pomona Division in 1961. In his 15 years with this division he has a wide range of engineering experience from technology development to full-scale engineering design and transition to production for guidance and control sytems, fire control systems and tactical missiles. He was director of design engineering for the Pomona Division in 1976 when he transferred to the Convair Division in San Diego.

Dr. Beuligmann was Vice President of Research & *Engineering for Convair* during 1976–1978 and for the period of March 1985 to present. In this responsibility, he directs the efforts of 1600 professional, technical and support personnel involved in the development of cruise missiles and aircraft systems.

For six years beginning October 1978 he directed the acquisition and management of large superconducting magnet programs. Six development and fabrication programs ranging from $5 million to $40 million were accomplished. General Dynamics became the most experienced U.S. supplier of large superconducting magnets for Fusion, Isotope Separation, and Magnetohydrodynamics (MHD) having won and successfully delivered 70 percent of the U.S. business in this area. Beginning in 1982 he directed the efforts of the Convair superconducting magnet team on contracted and company funded tasks on the Superconducting Super Collider dipole magnet developments beginning in 1982.

Dr. Beuligmann served on the Magnetic Fusion Advisory Committee of Department of Energy in 1982–1983. From September 1984 he has been a member of the Board of Directors Applied Superconductivity Conference. From 1984 he has been a member of the Board of Directors of Fusion Power Associates.

STATEMENT OF DR. JOHN K. HULM, DIRECTOR OF CORPORATE RESEARCH, WESTINGHOUSE R&D CENTER, PITTSBURGH, PA; ACCOMPANIED BY DR. CORD-HENRICH DUSTMANN, MARKETING & DEVELOPMENT, SUPER-CONDUCTING MAGNETS, POWER GENERATION DIVISION, BROWN, BOVERI & CIE AG, MANNHEIM, FEDERAL REPUBLIC OF GERMANY

Dr. HULM. I'm testifying on behalf of three industrial consultants to the Magnet Selection Advisory Panel; Dr. Raymond Beuligmann, from General Dynamics Corp.; Dr. Cord-Henrich Dustmann, who's sitting on my right, from the Brown, Boveri Co.; and I'm from Westinghouse.

We were invited to serve as industrial consultants to the Magnet Selection Advisory Panel to assist in the selection of the SSC magnet type from a set of five proposed magnet styles. The panel met for 4 days, August 25 to 28, 1985, and we were able to be present and to hear all of the testimony from proponents of the various styles, and from members of the SSC Central Design Group. We also participated in the executive sessions of the panel. We were able at all times to ask questions of the proponents and of the panel members. We were consulted by the panel throughout the executive sessions.

The Panel charged us, the industrial consultants, to comment on those factors related to all aspects of industrial production of the SSC magnets, with specific reference to design C and D—which is shown, by the way, as I'm sure you realize, design C, ours is on the left, the Texas accelerator design, and the design of D, the cosine theta design on the right.

We addressed our comments to four items; defining the elements of an R&D phase, and the respective status of maturity of design C and D, in successfully completing this R&D phase; second, to determine the viability of transitioning either design C and D successfully into industry for full-rate production, the number of magnets required.

Third, we recommended steps for involvement by industry with the SSC magnet development group so that an orderly transition of technology, sufficient to permit competitive bidding on the production magnets, could be achieved. And fourth, to compare the costs to develop and the costs to produce magnet design C and D.

The industrial consultant's report was submitted to the Panel, and became appendix G of the Advisory Panel report. I would like to read appendix G, if that's permissible, Mr. Chairman. It's quite short.

Mr. **Fuqua**. All right.

Dr. **Hulm**. As industrial consultants to the Magnet Selection Advisory Panel, we were asked to comment on those factors relating to all aspects of industrial production of the SSC magnets, with specific reference to designs C and D. We preceived the following major factors to be relevant to support the MSAP deliberations.

First, R&D phase. In our definition, the research and development phase is finished when the following are completed: material specifications, component detail design and testing, analyses, tool design, manufacturing processes, and prototype testing. We are in unanimous agreement that on this definition, the cosine theta style magnet is at a more advanced state of development than the superferric style for the following reasons.

The cosine theta style has an extensive base of R&D, testing, production and operating knowledge. More than 1,000 units have been incorporated in a large machine which is in successful operation. Extensive R&D has continued to refine this design in the past several years. We believe that the cosine theta design is in fact a mature technology.

A very limited data base exists for the superferric design style magnet. The first long superferric magnet will be tested in the first quarter of fiscal year 1986. It is our conclusion that the superferric style magnet technology is not mature. There are more unknowns in the superferric style design. This should be interpreted as a somewhat higher risk and longer R&D schedule needed for the superferric design. It is our judgment that the superferric style will need at least 2 years more of R&D development time than the cosine theta style design.

Production phase. We conclude that either style design in its present state of development can be produced in industry and achieve the production rates specified in the Central Design Group plan. Manufacturing studies have already been performed by General Dynamics, Westinghouse and Brown Boveri. General Dynamics has assembled one 1 meter magnet and one 28 meter magnet to the superferric style. Brown Boveri has already built eight magnets of the cosine theta style, four for the Brookhaven RHIC and four for HERA at DESY. Thus we conclude that from the point of view of producibility there is no reason to choose one style over the other.

It is our view that the production rate required by the Central Design Group plan can be successfully met, providing the following involvement with industry is achieved. The current level of industrial involvement should be increased in order to meet the present Central Design Group schedules. Industry should have the experience of doing the production plan and assisting the magnet development laboratories in the detailed design, fabrication, and testing of prototype magnets prior to the preproduction phase.

Second, industry must have the experience of doing the tool design, tool fabrication, magnet fabrication of the preproduction magnets in their own shops prior to the order of production contracts. The deliveries of production magnets per the Central Design Group plan can start 12 months after production contract award.

Last, costs and schedules. We believe that the Central Design Group cost estimates are sufficiently accurate to support the decision of selecting the magnet style for the SSC at this time. There is a higher degree of cost and schedule uncertainty with the superferric style magnet. The contingency factors applied for the two magnet styles by the CDG are relatively close. We feel that the cost contingency factor for the superferric style should be greater than stated, due to the higher degree of uncertainty both in cost and development schedules.

As an example of the higher uncertainty of production costs for superferric we note that the cosine theta style coil can be warm tested for field quality prior to insertion in the yoke. The superferric style cannot be warm tested in a similar manner due to the nonlinear field dependency for the iron.

Therefore, the quality of superferric windings can only be verified in a final cool down cryogenic test. This type of in-process test cited as possible for the cosine theta magnet is very important in reducing costs in production. We draw attention to this difference as support for the argument of having a higher cost contingency factor for the superferric style design.

That concludes my remarks, Mr. Chairman.

[The prepared statement of Mr. Hulm follows:]

24 October 1985

The Honorable Don Fuqua
Chairman
U. S. House of Representatives
Committee on Science & Technology
Suite 2321 Rayburn House Office Building
Washington, D. C. 20515

Dear Mr. Fuqua:

We, Dr. Raymond F. Beuligmann, Dr. Cord-Henrich Dustman, and Dr. John K. Hulm were invited to serve as industrial consultants to the Magnet Selection Advisory Panel (MSAP) to assist in the selection of the SSC magnet type from a set of five proposed basic magnet styles. The panel met for four days, August 25-28, 1985 and we were present and heard all of the testimony from proponents of the various styles and from members of the SSC Central Design Group. We participated in the executive sessions of the panel. We were able at all times to ask questions of the proponents and of the panel members. We were consulted by the panel throughout these executive sessions. The panel charged us, the industrial consultants, to comment on those factors relating to all aspects of industrial production of the SSC magnets, with specific reference to design C and D. We addressed our comments to:

(1) Defining the elements of an R&D phase and the respective status of maturity of designs C and D in successfully completing this R&D phase.

(2) Determining the viability of transitioning either design C and D successfully into industry for full-rate production.

(3) Recommending steps for involvement by industry with the SSC magnet development groups so that an orderly transition of technology sufficient to permit competitive bidding on production magnets could be achieved.

(4) Comparing the costs to develop and the costs to produce magnet designs C and D.

The industrial consultants report was sumitted to the panel and became Appendix G of the MSAP report. Appendix G is attached herein.

Sincerely,

Dr. R. F. Beuligmann Dr. C. H. Dustmann Dr. J. K. Hulm

APPENDIX G. STATEMENT OF THE INDUSTRIAL CONSULTANTS

As industrial consultants to the Magnet Selection Advisory Panel, we have been asked to comment on those factors relating to all aspects of industrial production of the SSC magnets, with specific reference to designs C and D. We perceive the following major factors to be relevant to support the MSAP deliberations.

R&D Phase

In our definition, the Research and Development phase is finished when the following are completed: material specifications, component detail design and testing, analyses, tool design, manufacturing processes, and prototype testing. We are in unanimous agreement that on this definition, the cos θ style magnet is at a more advanced state of development than the superferric style magnet, for the following reasons.

The cos θ style has an extensive base of R&D, testing, production and operating knowledge. More than 1000 units have been incorporated in a large machine which is in successful operation. Extensive R&D has continued to refine the cos θ style design in the past several years. We believe that the cos θ design is a mature technology.

A very limited data base exists for the superferric style magnet. The first long superferric magnet will be tested in the first quarter of FY 1986. It is our conclusion that the superferric style magnet technology is not mature. There are more unknowns in the superferric style design. This should be interpreted as higher risk and longer R&D schedule needed for the superferric style.

It is our judgment that the superferric style will need at least two years more R&D development time than the cos θ style design.

Production Phase

We conclude that either style magnet design in its present state of development, can be produced in industry and achieve the production rates specified in the CDG plan. Manufacturing studies have already been performed by General Dynamics, Westinghouse and Brown Boveri. General Dynamics has assembled one 1 m magnet and one 28 m magnet of the superferric style. Brown Boveri has already built eight magnets of the cos θ style, four for the Brookhaven RHIC and four for HERA at DESY. Thus, we conclude that from the point of view of producibility there is no reason to chose one style over the other.

It is our view that the production rate required by the CDG plan can be successfully met, provided that the following involvement with industry is achieved:

1. The current level of industrial involvement should be increased in order to meet the present CDG construction schedules. Industry should have the experience of doing the production plan and assisting the magnet-development laboratories in the detail design, fabrication, and testing of prototype magnets prior to the preproduction phase.

2. Industry must have the experience of doing the tool design, tool fabrication, and magnet fabrication of the preproduction magnets in their own shops prior to production contract awards. The deliveries of production magnets per the CDG plan can start 12 months after production contract award.

Costs and Schedules

We believe that the CDG cost estimates are sufficiently accurate to support the decision of selecting the magnet style for the SSC at this time. There is a higher degree of cost and schedule uncertainty with the superferric style magnet. The contingency factors applied for the two magnet styles by the CDG are relatively close. We feel that the cost contingency factor for the superferric style should be greater than stated, due to the higher degree of uncertainty both in cost and development schedule.

As an example of the higher uncertainty of production costs for style C, we note that the cos θ style coil can be warm tested for field quality prior to insertion into the yoke. The superferric style cannot be warm tested in a similar manner due to the non-linear field dependency for the iron. Therefore, the quality of superferric windings can only be verified in a final cryogenic test. This type of in-process test cited as possible for the cos θ magnet is very important in reducing costs in production. We draw attention to this difference as support for the argument of having a higher cost contingency factor for the superferric style design.

C.H. Dustmann, Brown Boveri

R.F. Beuligmann, General Dynamics

J.K. Hulm, Westinghouse

Mr. Fuqua. Thank you very much, Dr. Hulm.

We'll now hear from Mr. Rohrer.

[The biographical sketch of Mr. Rohrer follows:]

E. Parke Rohrer, P.E.

Birth: June 22, 1924 Lancaster County, PA.

Education: B.S.M.E. New York University, NY.

Professional License: Pennsylvania & California (Both by examination).

Professional Experience: Most recent first.

1984-date Project Manager Construction of multi-purpose Complex JAARS Center, Waxhaw, NC.

1977-1983 Brookhaven National Laboratory, Long Island, NY.

1981-83 Deputy Director Colliding Beam Accelerator Project.

1977-81 Director Design & Construction of Conventional Facilities for Intersecting Storage Accelerator.

1961-1976 Daniel, Mann, Johnson and Mendenhall (DMJM) International consulting architectural engineering firm.

1974-76 V.P. Director of Regional Offices 10 Branch Offices from Honolulu to Washington, DC.

1968-74 V.P. DMJM—General Manager Joint Venture of four Firms responsible for Design & Construction (AEM) of Fermi National Accelerator Laboratory Conventional Facilities.

1966-68 Chief Engineer—Home office Daniel, Mann, Johnson and Mendenhall, Los Angeles, CA.

1961-66 Far East Manager DMJM Tokyo, Japan, Master Planned, designed, and managed construction for all Military Facilities in Japan, Korea, Taiwan and Okinawa for all Branches of Services.

1957-1961 General Supervisor—Rohr Corporation, Riverside, CA. Responsible for Conventional and Manufacturing Facilities Design and Construction in manufacture of metal-bonded honeycomb structures.

1952-1957 Project Engineer—Armstrong Cork Company, Lancaster, PA Central Engineering Department.

1946-1952 Formal Education.

1943-1946 U.S. Army Air Corps.

STATEMENT OF E. PARKE ROHRER, PRESIDENT, ROHRER ASSOCIATES, INC., WAXHAW, NC; ACCOMPANIED BY KEITH BULL, PROJECT LEADER FOR UNDERGROUND FACILITIES, RTK, OAKLAND, CA

Mr. Rohrer. Mr. Chairman, you have asked me to address the magnet dependent conventional construction costs for the SSC, as developed by the central design group. Although there are many magnet dependent conventional construction items, such as utilities, et cetera, I will concentrate on the major magnet dependent item, which is the collider tunnel enclosure. In order to furnish the DOE with a realistic, accurate cost estimate of a collider/tunnel, which was not site specific, the central design group and its architect-engineer came up with the median site concept. A median site was created by utilizing main ring sectors taken from four differing geological regions (fig. 1).

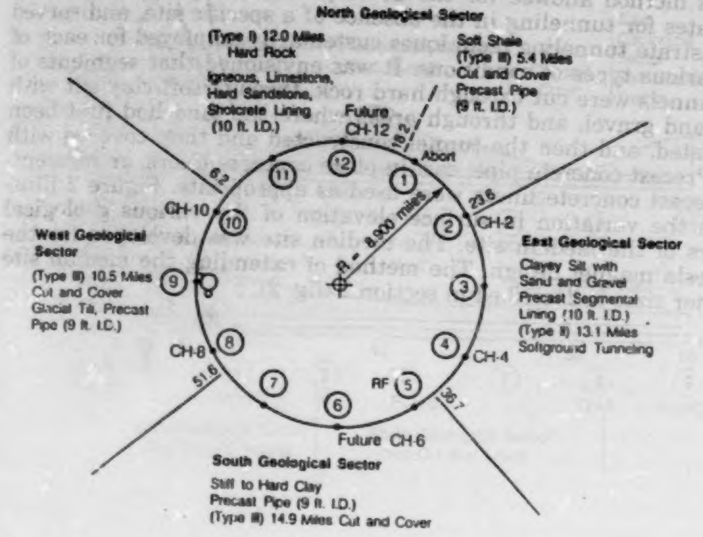

North Geological Sector
(Type I) 12.0 Miles
Hard Rock
Igneous, Limestone,
Hard Sandstone,
Shotcrete Lining
(10 ft. I.D.)
Soft Shale
(Type III) 5.4 Miles
Cut and Cover
Precast Pipe
(9 ft. I.D.)
Future
CH-12
18.2
Abort
6.2
23.6
CH-10
CH-2
R = 8,900 miles
West Geological
Sector
(Type III) 10.5 Miles
Cut and Cover
Glacial Till, Precast
Pipe (9 ft. I.D.)
East Geological Sector
Clayey Silt with
Sand and Gravel
Precast Segmental
Lining (10 ft. I.D.)
(Type II) 13.1 Miles
Softground Tunneling
CH-8
CH-4
51.6
RF
36.7
Future CH-6
South Geological Sector
Stiff to Hard Clay
Precast Pipe (9 ft. I.D.)
(Type III) 14.9 Miles Cut and Cover
1
2
3
4
5
6
7
8
9
10
11
12
XBL 844-1187

Fig. 1. The SSC main ring tunnel types in relation to the four hypothetical geological sectors and their composition. Mileage around the perimeter, clock position and the position of each collision hall are also indicated for a ring of 56 miles circumference.

This method allowed for the development of representative cost estimates for tunneling in the absence of a specific site, and served to illustrate tunneling techniques customarily employed for each of the various types of conditions. It was envisioned that segments of the tunnels were cut through hard rock, through soft clay silt with sand and gravel, and through areas where the land had first been excavated, and then the tunnel constructed and then covered with soil. Precast concrete pipe, cast-in-place concrete liners, or segmented precast concrete liners were used as appropriate. Figure 2 illustrates the variation in surface elevation of the various geological sectors of the median site. The median site was developed for the 6½ tesla magnet design. The method of extending the median site to other sizes is described in section 2 (fig. 2).

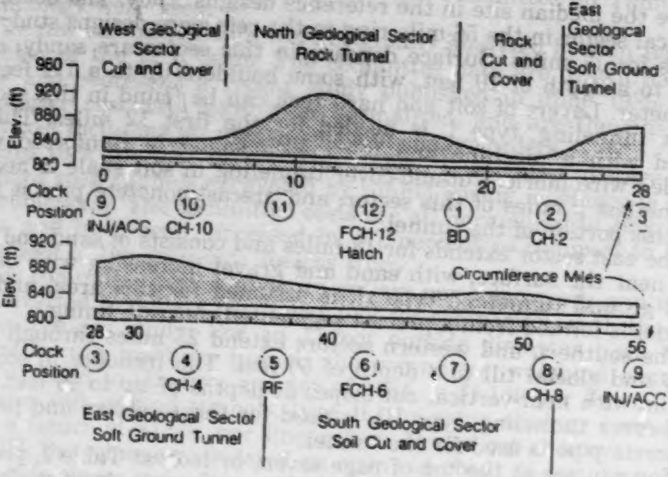

West Geological Sector Cut and Cover
North Geological Sector Rock Tunnel
Rock Cut and Cover
East Geological Sector Soft Ground Tunnel
960
920
880
840
800
Elev. (ft)
0
10
20
28
Clock Position
9
10
11
12
1
2
3
INJ/ACC
CH-10
FCH-12 Hatch
BD
CH-2
Circumference Miles
920
880
840
800
Elev. (ft)
28
30
40
50
56
Clock Position
3
4
5
6
7
8
9
CH-4
RF
FCH-6
CH-8
INJ/ACC
East Geological Sector Soft Ground Tunnel
South Geological Sector Soil Cut and Cover

Fig. 2. Profile of assumed surface topography around the circumference of the main ring tunnel indicating the relationship between circumferential distance in miles and clock position and their joint relationship to main geological features and tunnel construction methods. Positions of the collision halls, rf acceleration section, injection to the SSC main ring, and beam dump are given to illustrate the nature of the overlying strata at these points (and thus assumed elevations). These features impact on construction costs and methods.

In an effort to reduce the time, I'll move on to page 4 and describe the median site in the reference designs study. The north geological sector in the 56-mile ring in the reference designs study extends for 17 miles. Surface deposits in this sector are sandy, silty clay to a depth of 10 feet, with some boulders up to a 1½ feet in diameter. Layers of soft and hard rock can be found in this sector. Rock tunneling, type I, is needed for the first 12 miles. This is bored with a machine and lined with shotcrete reinforced with welded wire fabric. Cut-and-cover tunneling in soft shale is needed in the last 5 miles of this sector, and precast concrete pipe is used for this portion of the tunnel.

The east sector extends for 13 miles and consists of sand and clay silt near the surface, with sand and gravel increasing with depth. Soft ground tunneling, type II, is assumed for this area, and the tunnel is formed from a precast segmented concrete lining.

The southern and western sectors extend 25 miles through hard clay and glacial till to a depth of 50 feet. The trenches in soil are stable with near-vertical cut slopes at depths of up to 60 feet. Cut-and-cover tunneling, type III, is used for these sectors and precast concrete pipe is used for the tunnel.

You can see at the top of page seven, or look at Table I, you can see the relative amounts of the various types, in footage, for the various types of construction. Both under the columns A and B and then over on C and C* you can see that the total circumference then is 57.2 miles for the D type and 106.9 for the C style magnet.

Table I
Length of Typical Tunnel Segments

Design Style	A, D	B	C, C*
Type I	64,806	70,442	121,160
Type II	70,722	76,872	132,220
Type III	166,317	180,779	310,940
Circumference (feet)	301,845	328,093	564,320
Circumference (miles)	57.2	62.1	106.9

Moving along to page 10 of my submitted document, under unit costs in the middle of the page, you can see that the A/E firm developed unit costs for the three different tunnel types by a careful evaluation of the appropriate method of construction in each case. By assembling information on materials and labor requirements, rate of advance, et cetera, Parsons Brinckerhoff provided a basis for a cost estimate of the tunnels. This information was combined with the costs for access shafts, et cetera, and auxilliary buildings, to form an overall cost for the collider ring.

Recently another A/E firm, RTK, has been engaged. One of their first tasks was to consider the cost of tunnels such as those used in the reference design study. RTK chose to examine the data from a variety of completed tunnels. For the analysis, case histories, and data on 84 tunnels used by the National Committee on Tunneling Technology were used.

The raw committee data were originally analyzed by Don Rose, a member of the RTK team. The committee data are drawn nationwide and represent a recent study published in June 1985. The committee cost data have been normalized, and are the final as-built cost including all paid claims and change orders.

Hard rock tunnels, type I. The USNCTT weighted average cost for hard rock tunnels excavated by tunnel boring machines is $323 per cubic yard. The committee costs are all normalized to July 1982 costs, and have been increased by 3.7 percent to compare to 1984 costs used in the reference designs study.

This committee cost is given in dollars per cubic yards and must be converted to dollars per linear foot for comparison with the reference designs study. For an 11-foot outside diameter hard rock tunnel boring machine tunnel, the committee weighted average cost, updated to the first quarter of 1984, is $1,180 per linear foot.

Under soft ground tunnels, type II, the same analogy comes up with a figure of $1,095 per linear foot. Under cut-and-cover costs, type III, the scheme considered an open cut about 45 feet deep with steep side slopes open for a relatively short time. These slopes are assumed stable in all weather conditions year round, provided no ground water problems exist.

An unusually wide bottom width is provided to allow special vehicles to carry precast pipe along the side of the finished work. The precast pipe would be carried from the plant to a point near to the excavation, a distance of up to several tens of miles. The excavation work lends itself to mass production work using innovative excavators or conventional scrapers and tractors.

Then concluding that section, RTK believes the cut/cover tunnel will cost $873 per linear foot for the example studies. But the average cost for all cut-and-cover costs, type II, described is estimated at $780 per linear foot.

The recent evaluation by RTK can be conveniently compared to the earlier work by looking at table II. There's an excellent agreement between these independent estimates by experienced A/E firms. You'll see at the top of page 13, table II, and there you will see that the Central Design Group took the value of $930 per linear foot.

Table II
Unit Cost Estimates for Tunnel Types
($ Per Linear Foot)

	RDS	RTK	CDG Value
Main Ring Tunnel - Type I	1,150	1,167; 1,180	1,160
Main Ring Tunnel - Type II	1,100	1,095	1,100
Main Ring Tunnel - Type III, avg	755	780	770
Weighted Avg., Types I, II, III	920	-	930

The total Conventional Facility costs for the Collider Ring WBS 1.4.1 are shown for the five designs in Table III.

In conclusion I would like to say that the SSC Central Design Group, in its presentation to the Magnet Selection Advisory Panel, used the median site weighted average of $930 per linear foot of tunnel as the basis for deriving the total tunnel costs applicable to the various magnet designs.

Dr. John Rees, a panel member for SLAC, and myself were assigned to the conventional facilities aspect of the SSC Magnet Advisory Panel. We both believe the figure of $930 per linear foot, for determining the total tunnel cost for a representative site, not a specific site on which the SSC could possibly be constructed, is both prudent and realistic.

Thank you.

[The prepared statement of Mr. Rohrer follows:]

TESTIMONY BY E. PARKE ROHRER A MEMBER OF THE MAGNET SELECTION ADVISORY PANEL FOR THE SUPERCONDUCTING SUPER COLLIDER

E. Parke Rohrer, P.E.
Consultant

Subcommittee on Energy Development and Applications
Committee on Science and Technology
United States House of Representatives

October 29, 1985

Mr. Chairman: You have asked me to address the magnet dependent conventional construction costs for the SSC (Superconducting Super Collider) as developed by the Central Design Group. Although there are many magnet dependent conventional construction items such as utilities, etc., I will concentrate on the major magnet dependent item which is the collider tunnel or enclosure. In order to furnish the DOE with a realistic accurate cost estimate of a collider/tunnel which was not site specific, the Central Design Group and its architect-engineer came up with the median site concept. A median site was created by utilizing main ring sectors taken from four differing geological regions. (See Fig. 1.)

This method allowed for the development of representative cost estimates for tunneling in the absence of a specific site, and served to illustrate tunneling techniques customarily employed for each of the various types of conditions. It was envisioned that segments of the tunnels were cut through hard rock (igneous, limestone, or hard sandstone), through soft clayey silt with sand and gravel, and through areas where the land had first been excavated, the tunnel constructed and then covered with soil. Precast concrete pipe, cast-in-place concrete liners, or segmented precast concrete liners were used, as appropriate. Figure 2 illustrates the variation in surface elevation of the various geological sectors of the median site. The median site was developed for the 6.5T magnet design. The method of extending the median site to other sizes is described in Section 2.

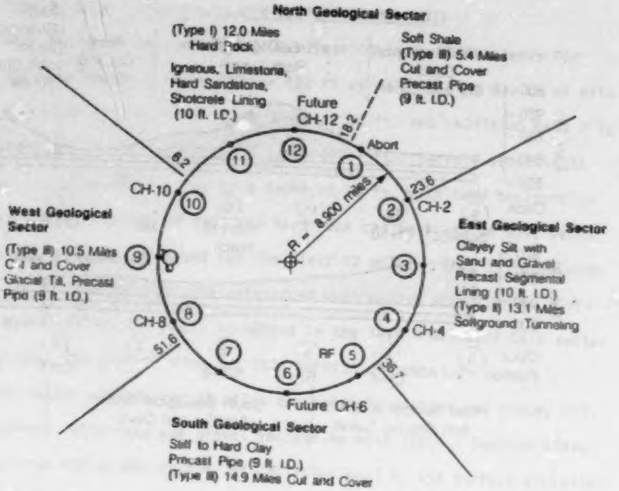

North Geological Sector
(Type I) 12.0 Miles
Hard Rock
Igneous, Limestone,
Hard Sandstone,
Shotcrete Lining
(10 ft. I.D.)
Soft Shale
(Type III) 5.4 Miles
Cut and Cover
Precast Pipe
(9 ft. I.D.)
Future
CH-12
18.2
Abort
6.2
23.6
CH-10
CH-2
R = 8.900 miles
West Geological
Sector
(Type III) 10.5 Miles
Cut and Cover
Glacial Till, Precast
Pipe (9 ft. I.D.)
East Geological Sector
Clayey Silt with
Sand and Gravel
Precast Segmental
Lining (10 ft. I.D.)
(Type II) 13.1 Miles
Softground Tunneling
CH-8
CH-4
51.6
RF
36.7
Future CH-6
South Geological Sector
Stiff to Hard Clay
Precast Pipe (9 ft. I.D.)
(Type III) 14.9 Miles Cut and Cover
1
2
3
4
5
6
7
8
9
10
11
12

Fig. 1. The SSC main ring tunnel types in relation to the four hypothetical geological sectors and their composition. Mileage around the perimeter, clock position and the position of each collision hall are also indicated for a ring of 56 miles circumference.

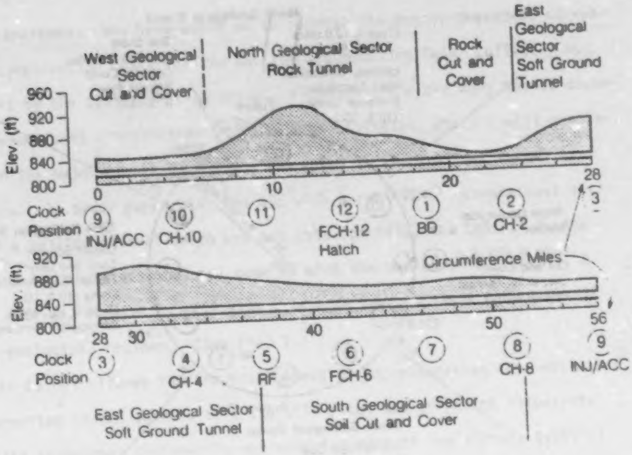


Fig. 2. Profile of assumed surface topography around the circumference of the main ring tunnel indicating the relationship between circumferential distance in miles and clock position and their joint relationship to main geological features and tunnel construction methods. Positions of the collision halls, rf acceleration section, injection to the SSC main ring, and beam dump are given to illustrate the nature of the overlying strata at these points (and thus assumed elevations). These features impact on construction costs and methods.

1. "Median Site" in the Reference Designs Study (RDS)

The north geological sector in the 56 mile ring in the RDS extends for 17 miles and varies from an elevation of 922 ft at mile 11.6 to 831 ft at mile 22. The beam dump is at mile 18.6, at depth of 30 ft, and collision hall 2 is at the eastern end of this sector at a depth of 17 ft. Surface deposits in this sector are sandy, silty clay to a depth of 10 ft, with some boulders up to 1.5 ft diameter. Layers of soft and hard rock can be found in this sector. Rock tunneling (Type I) is needed for the first 12 miles. This is bored with a machine and lined with shotcrete reinforced with welded wire fabric. Cut-and-cover tunneling in soft shale is needed in the last 5 miles of this sector and precast concrete pipe is used for this portion of tunnel.

The east sector extends for 13 miles and consists of sand and clayey silt near the surface, with sand and gravel increasing with depth. Surface elevation varies from 900 to 832 ft and, at collision hall 4, the surface elevation is 880 ft. Soft ground tunneling (type II) is assumed for this area, and the tunnel is formed from a precast segmented concrete lining.

The southern and western sectors extend 25 miles through hard clay and glacial till to a depth of 50 ft; the trenches in soil are stable, with near-vertical cut slopes, at depths up to 60 ft. Cut-and-cover tunneling (type III) is used for these sectors and precast concrete pipe is used for the tunnel.

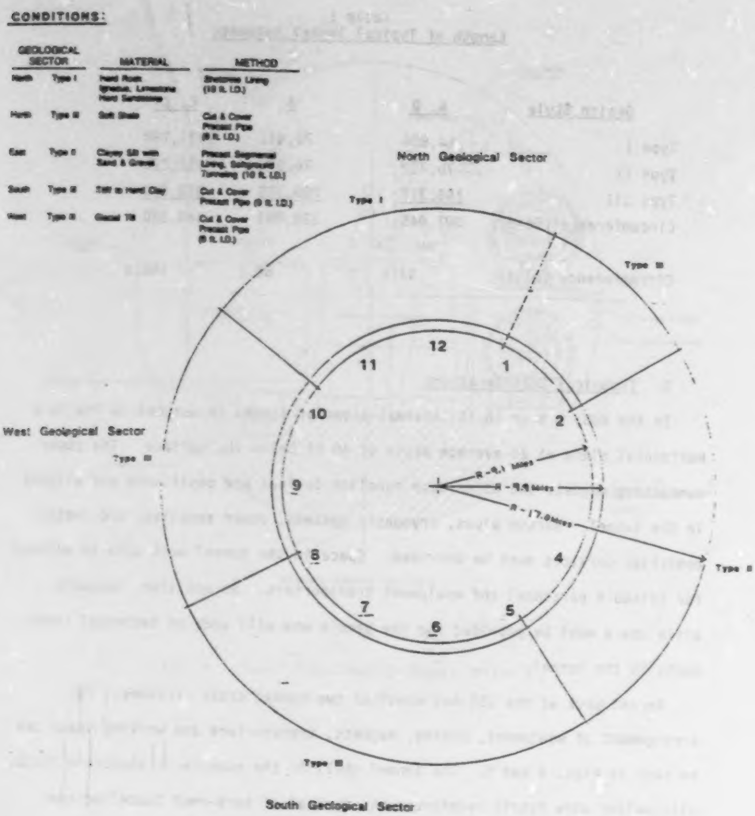
The ring is interrupted at six locations by interaction regions (where the beams collide for physics experiments) and by three utility straight sections.

Two of the former areas are left undeveloped to allow for future expansion of experimental opportunities, while the other four are sites of the experimental halls and associated facilities. The complex of buildings at each interaction region is designed to allow the transport and assembly of experimental equipment, and to provide for the undertaking of long-term experiments. The utility straight sections contain the rf accelerating cavities, the injection system for the incoming beam, and the beam abort apparatus. Appropriate buildings are associated with each of these functions, and equipment access to the tunnel is provided.

2. Extension of the "Median Site"

The Median Site concept was developed to provide a technical baseline for conventional systems in the RDS. The A/E firm, Parsons Brinckerhoff, prepared this model so that civil, structural, electrical and mechanical engineers could do a design study under "almost realistic" conditions. As described earlier, the model was done for a 56 mile ring, employing 6.5T magnets, and extended to larger circumferences as required by the utilization of lower field magnets.

In order to illustrate how the median site can be extended, another illustration has been created. Assuming that the same proportions of geological conditions prevail, Figure 3 shows how the varying segments might appear. The length of such segments are shown as in Table I.



CONDITIONS:

GEOLOGICAL SECTOR		MATERIAL	METHOD
North	Type I	Hard Rock Igneous, Limestone Hard Sandstone	Shotcrete Lining (10 ft. I.D.)
North	Type II	Soft Shale	Cut & Cover Precast Pipe (8 ft. I.D.)
East	Type II	Clayey Silt with Sand & Gravel	Precast Segmental Lining, Softground Tunneling (10 ft. I.D.)
South	Type III	Stiff to Hard Clay	Cut & Cover Precast Pipe (8 ft. I.D.)
West	Type III	Glacial Till	Cut & Cover Precast Pipe (8 ft. I.D.)

North Geological Sector
Type I
Type III
West Geological Sector
Type III
Type II
South Geological Sector
Type III
12
1
2
4
5
6
7
8
9
10
11
R - 9.1 Miles
R - 9.9 Miles
R - 17.0 Miles

Fig. 3. Extension of Median Site Concept to Three Ring Sizes.

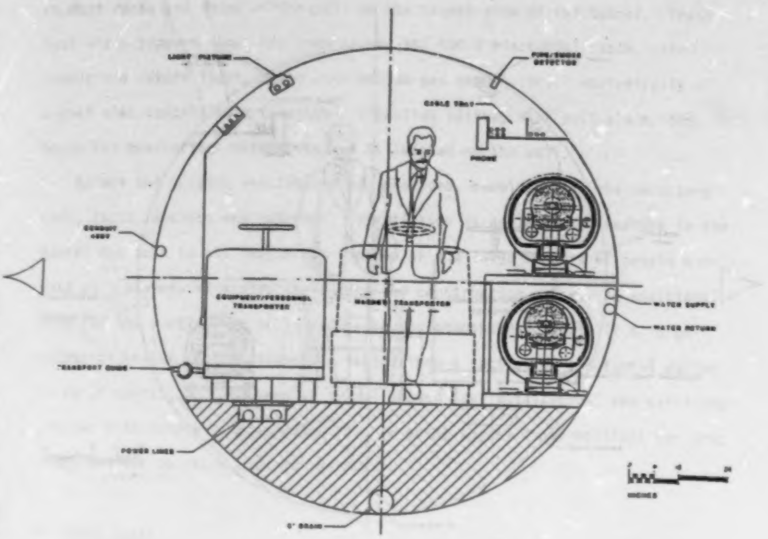
Table 1
Length of Typical Tunnel Segments

Design Style	A, D	B	C, C*
Type I	64,806	70,442	121,160
Type II	70,722	76,872	132,220
Type III	166,317	180,779	310,940
Circumference (feet)	301,845	328,093	564,320
Circumference (miles)	57.2	62.1	106.9

3. Technical Considerations

In the RDS, a 9 or 10 ft internal diameter tunnel is assumed to lie in a horizontal plane at an average depth of 40 ft below the surface. The superconducting magnets and other beam handling devices are positioned and aligned in the tunnel. Vacuum pipes, cryogenic systems, power supplies, and instrumentation services must be provided. Space in the tunnel must also be allowed for suitable personnel and equipment transporters. In addition, adequate aisle space must be provided for the people who will work on technical components in the tunnel.

Recent work at the CDG has examined two tunnel cross sections. The arrangement of equipment, piping, magnets, transporters and working space can be seen in Figs. 4 and 5. The tunnel shell in the example is shotcrete lined, with welded wire fabric reinforcement, typical of hard-rock tunneling construction. A poured concrete floor results in a level, 8.3 ft wide working surface within a 9-10 foot circular cross section. Floor drainage is installed. Lighting fixtures and a cable tray are anchored in the roof and


LIGHT FIXTURE
FIRE/SMOKE DETECTOR
CABLE TRAY
PHONE
CONDUIT ASSY
EQUIPMENT/PERSONNEL TRANSPORTER
MAGNET TRANSPORTER
WATER SUPPLY
WATER RETURN
TRANSPORT GUIDE
POWER LINES
6" DRAIN
INCHES

TUNNEL CROSS SECTION

Fig. 4. Tunnel Cross Section Magnet Design D

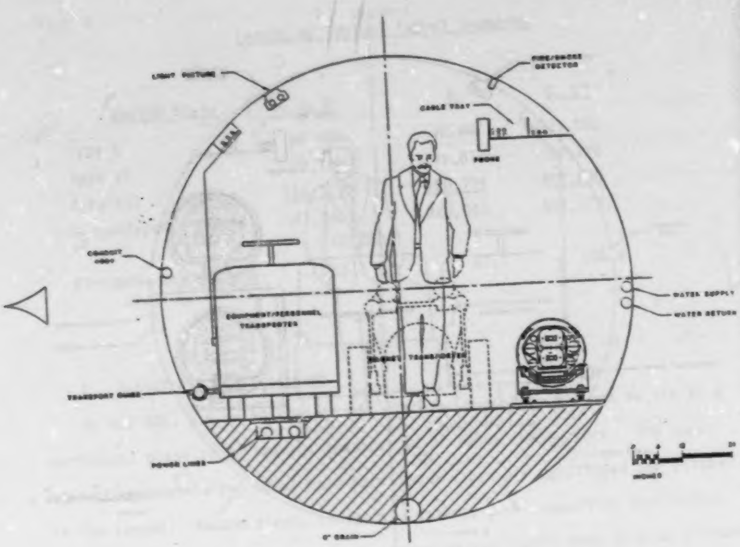

LIGHT FIXTURE
FIRE/SMOKE DETECTOR
CABLE TRAY
PHONE
CONDUIT
EQUIPMENT/PERSONNEL TRANSPORTER
MAGNET TRANSPORTER
WATER SUPPLY
WATER RETURN
TRANSPORT GUIDE
POWER LINES
6" DRAIN
INCHES

Fig. 5. Tunnel Cross Section Magnet Design C

conduit racks are fixed to the wall on the magnet side of the tunnel. These last items support lines for compressed gas, 480 V electrical cable, water supply and return lines, and a warm-helium gas return line. Periodically a signal area containing a telephone, signaling system, fire pull alarm, and space for monitoring instrumentation is located on the wall.

Normal and purging ventilation are provided, complete with the necessary fans, ducts, outlets and controls. Ventilation is an important feature in the tunnel due both to its length and because of the large numbers of people working at a variety of activities during the construction phase. An additional need for the ventilation is to replenish the atmosphere quickly if a large volume of helium were accidentally vented into a section of the tunnel during tests or operations. Matters of tunnel access for installation, and servicing coupled with safety consideration lead to using tunnel cross sections for this study similar to those used in the RDS.

4. Unit Costs

A) Tunnel

The A/E firm developed unit costs for the three different tunnel types by a careful evaluation of the appropriate method of construction in each case. By assembling information on materials and labor requirements, rate of advance, etc., Parsons Brinckerhoff provided a basis for a cost estimate of the tunnels. This information was combined with the costs for access shafts, exits, auxiliary buildings, etc., to form an overall cost for the collider ring.

Recently, another A/E firm, RTK (Raymond Kaiser Engineers, Tudor Engineering, Keller & Gannon-Knight), has been engaged. One of their first tasks was to consider the cost of tunnels such as those used in the RDS. RTK chose to examine the data from a variety of completed tunnels. For the analysis, case histories and data on 84 tunnels used by the U.S. National Committee on Tunneling Technology (USNCTT) were used. The raw USNCTT data were originally analyzed for the USNCTT by Don Rose, a member of the RTK team. The USNCTT data are drawn nationwide and rspresent a recent study published in June, 1985. The USNCTT cost data have been normalized and are the final as-built cost including all paid claims and change orders.

a. Hard Rock Tunnels (Type I). The USNCTT weighted average cost for hard rock tunnels excavated by tunnel boring machines (TBM's) is $323/CY. The USNCTT costs are all normalized to July, 1982, costs and have been increased by 3.7% to compare to 1984 costs used in the RDS. This USNCTT cost is given in $/CY and must be converted to $/LF for comparison with the RDS. For an 11-foot outside diameter hard rock TMB tunnel, the USNCTT weighted average cost, updated to the first quarter of 1984, is $1180/LF.

b. Soft Ground Tunnels (Type II) The USNCTT weighted average cost for soft ground tunnels is $300/CY. The USNCTT costs are all normalized to July, 1982, costs and have been increased by 3.7% to compare to the RDS. This USNCTT cost is given in $/CY and must be converted to $/LF for [illegible]mparison with the RDS. For an 11-foot outside diameter soft ground tunnel, the USNCTT weighted average cost updated to the first quarter of 1984, is $1,095/LF.

c. Cut and Cover Costs (Type III) The scheme considered an open cut about 45 feet deep with steep side slopes open for a relatively short time. These slopes are assumed stable in all weather conditions the year around, provided no groundwater problems exist. An unusually wide bottom width is provided to allow special vehicles to carry precast pipe alongside the finished work. The precast pipe would be carried from the plant to a point near to the excavation, a distance of up to several tens of miles. The excavation work lends itself to mass production work using innovative excavators, or conventional scrapers and tractors. Different bidders will no doubt select different methods and equipment. For this report, the cut/cover scheme shown in the RDS has been evaluated by an RTK study with reference to federal, state and private agencies for costs comparable of work done using conventional equipment. RTK believes the cut/cover tunnel will cost $873/LF (first quarter 1984 prices) for the example studied. The average cost for all cut and cover costs (Type III) described is estimated as $790/LF.

d. Summary The recent evaluation by RTK can be conveniently compared to the earlier work by looking at Table II. There is excellent agreement between these independent estimates by experienced A/E firms.

3) Ramps/Slots

There are several differences that arise from the choice of magnetic field and corresponding style of magnet. The different circumferences have been addressed earlier, although there are additional items that must be considered. First of all, the allowance for site infrastructure (such as roads, utilities) must scale with the circumference. In addition, the number of exits will be increased in proportion to the increased tunnel length, thereby keeping fixed the distance between exits within the tunnel.

Table II

Unit Cost Estimates for Tunnel Types

($ Per Linear Foot)

	RDS	RTK	CDG Value
Main Ring Tunnel - Type I	1,150	1,167; 1,180	1,160
Main Ring Tunnel - Type II	1,100	1,095	1,100
Main Ring Tunnel - Type III, avg	755	780	770
Weighted Avg., Types I, II, III	920	-	930

The total Conventional Facility costs for the Collider Ring WBS 1.4.1 are shown for the five designs in Table III.

In contrast to the position taken during the RDS, the same number of refrigerator/compressors stations (12) will be used in all the configurations. This will change the distance between stations from 5 miles in Design A to almost 9 miles in Design C.

Because it is envisioned that the very long superferric magnets will be assembled at four places adjacent to the collider ring, a number of adjustments must be made to the plan for a campus works area, and to the approach used for getting the 380 ft magnets into the ring. One might expect to need more works building space due to the assembly areas being dispersed.

The predominant effect of the long magnets is to require access ramps or slots at four locations to move assembled magnets down into the tunnel. RTK has done a study of this approach using a depth appropriate for soft ground tunnels. In FY84 dollars they have established a cost of $5.7M each for a ramp scheme and $3.4M each for a vertical slot scheme.

Table III
Conventional Facility Cost Comparison Summary
(FY 84K$)

	MAGNET STYLE:	A	B	D	C	C*
	PARAMETER VALUES:					
	FIELD LEVEL, T	6.40	5.75	6.40	3.00	3.00
	CIRCUMFERENCE, MI	57.17	62.14	57.17	106.88	106.88
	(CIRCUMFERENCE, KM)	92.00	100.00	92.00	172.00	172.00
(WBS) 1.4.1	CONVENTIONAL FACIL. SYSTEMS,					
.1	LAND IMPROVEMENTS	15,300	16,631	15,300	28,605	28,605
.2.1	TUNNEL TYPE I	88,038	95,693	88,038	164,592	164,592
.2.2	TUNNEL TYPE II	90,249	98,097	90,249	168,726	168,726
.2.3	TUNNEL TYPE III	154,292	167,709	154,292	288,459	288,459
.2.4	TUNNEL (OTHER ELEMENTS) (CRYO, BM DUMP, RF, ETC)	13,927	13,927	13,927	13,927	13,927
.3	CRYOGENIC FACILITIES	7,998	7,998	7,998	7,998	7,998
.4	SUPPORT BUILDINGS	1,750	1,902	1,750	3,272	3,272
.5	UTILITIES	38,822	42,198	38,822	72,581	72,581
.6	ACCESS SHAFTS	0	0	0	13,540	13,540
	TOTAL CONVEN. FACILITIES	410,376	444,154	410,376	761,700	761,700

The SSC Central Design Group in its presentation to the magnet selection advisory panel used the median site weighted average of $930 per linear foot of tunnel as the basis for deriving the total tunnel costs applicable to the various magnet designs.

Dr. John Rees, a panel member for SLAC, and myself were assigned to the Conventional Facilities aspect of the SSC Magnet Advisory Panel. We both believe the figure of $930 per linear foot for determining the total tunnel cost for a representative site on which the SSC could possibly be constructed is both prudent and realistic.

E. Parke Rohrer

EPR:lcm

Mr. Fuqua. Thank you very much, Mr. Rohrer.

Dr. McIntyre mentioned that civil engineers at the Texas consortium had invented some new tunneling technology that promises to significantly increase tunneling rates and reduce the costs. Are you familiar with this technology, and do you agree with—did you have a chance to look at that in your observations?

Mr. Rohrer. Sir, Mr. Chairman, I have read what they had in their volume C, preliminary tunnel cost estimates for the SSC project at six Texas sites. And I had studied that. And they talk about the work of costran, a computer program, and then they talk about work and studies to increase muck handling and so on.

All those items—and then there was a panel convened to evaluate the reduced rate—for the increased rate of muck handling. And that panel, chaired by Dave Hammond, a tunneling and construction expert, had concluded that there was no particular merit in those proposals.

Now, what I have found in the volume C, is a study that I have not seen any reason to change my estimate, I think that the desire to reduce tunnel costs is admirable, but I don't see any realistic reason to change at this time. I have not seen any proof to change our estimate.

Mr. Fuqua. Do you think it might have some applicability in the future?

Mr. Rohrer. I think that what I have seen is a hope and a wish and a desire to have a lower cost, but I do not see any reason to feel that there is anything beyond what we have seen in other tunneling results and experienced tunneling consultants and engineers.

Mr. Barton. Mr. Chairman, would you yield on that point, please?

Mr. Fuqua. Certainly.

Mr. Barton. I may be misinformed, but I have information that there are tunnels being built right now for $350 to $500 a foot. Is my information incorrect?

Mr. Rohrer. No, your information is correct. I'm very familiar with that situation. Do you also have information, sir, as to the condition of those contractors and their willingness to take other contracts at that cost?

Mr. Barton. Well, the bottom line here is we want to get the most possible bang for the least possible buck. And if we've got some contractors that feel they need to put bread on the table and are willing to do it for $350 to $400 a foot, I think we ought to allow them to do that.

Dr. Rohrer. It's my information that all three are losing money. One, $2 million, over 50 percent of its bid price is lost. And another general manager of one of the other firms would not take another job on a nonunion in that situation. He would bring in his union people and take it in an entirely different approach. I have thoroughly investigated those situations. I would not use those prices, sir, because I think that when the contractors look at a Federal specification—those were not Federal jobs—when they looked at a Federal specification with the safety requirements—and it's true that Davis-Bacon has not been mentioned in any of these discussions, and it is also true that a Davis-Bacon determination could go open shop in certain areas.

You have in Texas probably one-third of your communities—of your counties are union, and the other two-thirds are nonunion. Approximately 80 counties in Texas are union.

Now, whether you happen to fall within those areas, and a Davis-Bacon determination was made to say this should be comparable to union rates, or whether it would be open, the branch chief for the Department of Labor told me that he would suggest that we wait until the time that a contract document was out for bid, or I mean ready to go out to bid, before a determination could be made. He could not guarantee that it would be union, but he also could not guarantee it would be nonunion.

So, this situation on these types of contracts, with the percentage profit, if a contractor is not in business to make money, he has absolutely no excuse for being in business. And therefore, it is my opinion that what we have seen is an unusual situation there that would be not duplicated.

Mr. BARTON. I just wanted to know——

Mr. FUQUA. I can assure you, Mr. Barton, that the Federal Government couldn't build an outhouse. [Laughter.]

Mr. BARTON. I just wanted the record to show that there are tunnels being built for less than what's in this study, that's all.

Mr. ROHRER. Yes, sir.

Mr. FUQUA. Dr. Hulm, in your statement you state that the superferric style will need at least 2 more years R&D time than the cosine theta style design. Is it worth putting additional funds into R&D into the superferric magnet?

Dr. HULM. I think if we could see at the end of the program——

Mr. FUQUA. The end of the tunnel?

Dr. HULM [continuing]. A great reduction in cost of the system, or some other advantage, then I would say yes. But there's no obvious reason for that. In fact, I think most of the people on the committee felt that probably the costs would tend to increase somewhat over the present estimates. So, I don't see any advantage with the high-field design having—as our selection, based on looking at those kind of factors. I don't know whether my colleague, Dr. Dustmann, wants to comment on that.

Dr. DUSTMANN. I totally agree with Dr. Hulm.

Mr. FUQUA. Dr. Sciulli, what were the cost estimates of the superferric magnets and the cosine theta magnets, and how were the estimates developed; specifically in the basis for development costs, fabrication costs, installation costs, testing costs, and maintenanc costs for each?

Dr. SCIULLI. The Central Design Group took on the burden of collating all costs. In some cases, some designs had different apertures, and that was a separate task group that looked at the magnet apertures in order to bring everything so that you were looking at not comparing apples and oranges.

There were tables of costs which one can go through, but basically it was broken down into the basic magnet costs itself, plus contingencies on the magnet system itself, the associated cryogenics power needs, and so on, associated with the magnets, and in addition the tunneling and conventional construction again associated with the magnets.

The conventional construction—only conventional construction and other costs that were deemed relevant to this study were those that were impacted by the magnets themselves.

Now, the actual cost, the bottom line after all of this, was that according to the central design group estimate, using, as was stated before, essentially the same contingency for the C and D magnets, which the Panel did not agree with.

Mr. FUQUA. Were all those costs verified?

Dr. SCIULLI. Those costs were done in consultation with the proponent laboratories, in the case of the magnet systems themselves. There were task groups that looked at the designs themselves, and there were people in the central design group who were versed in magnet issues, plus there was a technical magnet review panel consisting of the proponents and others that looked at the basic designs and interacted on the costs.

The bottom line—oh, I'm sorry, and there were two industrial consultants that also collaborated in breaking down those costs. And the bottom line estimate was that for the type C magnet, including all of these factors, was $2.183 billion for the type C, superferric, and $2.100 billion for the type D, cosine theta. That's using the $930 per linear foot that Mr. Rohrer referred to. So, the difference was $83 million. That's why I said the costs were comparable with some slight edge for the cosine theta design.

Mr. FUQUA. Dr. McIntyre, is the TAC group requesting further funding either from DOE or the central design group for continued work on the superferric magnet?

Dr. MCINTYRE. Yes, sir. We will be concluding our R&D program on the superferric design during the first half of fiscal 1986. That includes conducting tests on the long magnets, which are—the first one is being delivered today, and the second one is stated for delivery in early December.

During the period from about early December through the month of March we will be testing and evaluating those magnets or the variety of technical issues that we'll stand to learn from hose. We believe that's a very valuable R&D program, and that will bring to a conclusion the work that we're doing on the super-erric.

Mr. FUQUA. How much are you requesting from DOE?

Dr. MCINTYRE. Total support for that program is presently allo-ated at $750,000. That includes all of our manpower and all of the perating costs for our group. That is devoted to that. In parallel ith that effort, as I've stated in my testimony, the TAC will be amping up into a major role in the preparation of the high-field esign, and the carrying forward of several specific tasks on that.

I'd also point out that this ramping up of the work on the new esign, ramping down of our work on the superferric, is precisely form with what has happened about 9 months ago on the evolu-on of the cosine theta design. When the laboratory groups consoli-ted into the choice of design D for further work, the work at ookhaven on design B—I'm sorry, at Fermilab on design B, and e work at Brookhaven on design A continued, and was funded to ntinue on a ramp-down-mode up through about the present time.

A lot of good information has been learned out of that program that's relevant to design D and to the whole development of superconducting magnets, period. And the same is true of the work that we're now concluding on the superferric.

Mr. FUQUA. Do you think it would be worthwhile to keep spending public monies on the design that has not been chosen?

Dr. MCINTYRE. Emphatically I do, because the work that we are doing will—first of all, it has direct relevance to a number of other accelerator projects that DOE is considering at this time, including the Brookhaven booster, the Los Alamos meson-factory upgrades, and, as I said, in other applications in science and technology, including the superconducting light sources. So, I think there's high relevance for the superferric design in a number of applications.

To point that up, if you just take a look at the two designs, it's clear, I believe, that there is a lot of merit in the superferric given that from all technical points of view it is just as capable of performance for the collider requirements as the high field design. And, as you can see from the drawings on the board, it's more compact. And the CDG's own evaluations, the total magnet systems cost precisely half as much as they do for the high field designs.

So, for a number of other applications that are already in the consideration process within DOE, this design may be quite relevant.

Mr. FUQUA. You indicated in your statement that TAC did not agree with the central design group magnet decision. What specific disagreements do you have with it, and what are the technical bases for those disagreements? I know we never like to be on the losing end, but——

Dr. MCINTYRE. Yes, sir. If our disagreement did not go beyond simply being on the losing end, I would not have belabored your committee with it. On the whole, our imbalance, I think it is probably—I don't know quite how to put the total scope of technical issues that were borne out and were brought into the judgment on the two designs into perspective for the committee.

As Dr. Sciulli pointed out, or described in his testimony, this was very much a technical decision by technical experts. I can, if you wish, summarize some of the points of disagreement.

What I would emphasize, however, is that to my view, and I believe also to the panel's view—and they can stand to correct me, of course—the two designs, C and D, that had been prepared for the SSC, have been demonstrated to be attractive, viable designs. The SSC would work and work well with either of those two designs.

Their costs are comparable. Their state of development is comparable, although there we have some points of difference. Given that, the judgment between them is a close call. It is obviously a painful call for one of the parties involved. If we had made the call it would have been the other way, and we believe for justifiable reasons which I can list through for you.

I think the point of emphasis, however, is that we concur that the high-field design that has been chosen is a viable design, and will work and work well for the SSC. And that there is a necessity to make a decision on this matter and proceed on. And we're prepared to do that.

Mr. FUQUA. Mr. Barton.

Mr. **Barton**. Thank you, Mr. Chairman. It strikes me as rather odd that we're here today to review the state of high energy physics, and in that review to review the superconducting collider project, and as part of that the magnet design that's been chosen. And, Mr. Chairman, until you asked the specific question there had been no reference to the cost of the two finalists in the magnet design.

In response to your direct question, Dr. Sciulli did indicate that style D, or the high-field design, had a cost of $2.1 billion, and style C, or the TAC low-field design, had a cost of $2.183 billion. That's a difference of $83 million in one of the most expensive high energy physics projects that this country has yet undertaken.

I have spent an inordinate amount of time reviewing all the documents that went into making this decision. Dr. Tigner and Dr. Trivelpiece have been very forthcoming and provided me with that information. I have some very serious questions about the way the numbers were put together.

If you look—and since we weren't provided with it, I have the table 4 summary that the magnet design selection team used, and I've reviewed this in some depth. If you look at this and you determine that of the $2.183 billion, 50 percent of those costs are of the ow-field design are because of tunneling, and obviously the tunnel s larger. It is, I believe, 107 miles in circumference. Of the design hat was chosen, the tunneling cost is only approximately 28 perent.

Now, I don't argue with the expert, Mr. Rohrer, on tunneling, hat $350 to $450 may be too low per linear foot. Like you say, the 'ederal Government can't build anything cheaply. But I think it is ermissible to expect that we might be able to tunnel for less than ne $930 to as high as $1,200 per linear foot that's in this site esign selection.

And if that's true, if we can in fact build a tunnel for say $800 a near foot or $750 a linear foot, then the low field design is several illions of dollars less expensive, hundreds of millions of dollars ss expensive.

So, I would like an opportunity to—I don't want to belabor the nel's time—but I would like an opportunity to submit some very ecific questions as to cost and the way they were arrived at, with ur permission, if that's permissible.

Mr. **Fuqua**. Certainly.

Dr. **Sciulli**. Might I respond?

Mr. **Barton**. Sure.

Dr. **Sciulli**. One of the things that one must do, though, when e takes into—if one is going to make an assumption of a differ- tunnel cost, is to take into account the fact that the other ign also has a tunnel.

Mr. **Barton**. Sure.

Dr. **Sciulli**. If, for example,—I mean, at our meeting, at our el discussion, the TAC people proposed that a fairer estimate $700 per linear foot rather than $930 a linear foot. If you take, ording to their submission, the new cost, putting it into both ign D and design C, you find that the C design is $199.7 million D design is $198.6. So, even at $700 per linear foot, the D gn is still slightly ahead. And, as I said before, that does not

pages tightly bound

include any added contingency that this panel of technical experts thought should be added to the C design.

So, if you want to go substantially below $700 a linear foot, and say that Panel was wrong in saying you needed added contingency for the C design, then I think there's an argument. But to the Panel it was quite clear.

Mr. **Barton**. Well, Dr. Sciulli, I'm not indicating that the panel was wrong. You've got to make prudent choices, you've got to build in contingencies. I'm not questioning that fact. There are some things, though, that I do question. For example, one of the costs that was excluded was R&D. Somewhere in all of this mass of data the central design group made a decision to exclude R&D costs.

Now, I'm told that R&D cost on the low-field design per next year would be approximately $5 million if it had been chosen. R&D costs for the design that was chosen is $50 million.

Is that true or not true?

Dr. **Sciulli**. No, sir. I think that whatever design was chosen, that design would have gotten the bulk of the R&D funds and the other design would have been phased out. That would have been the natural—if the other design had been chosen, you would have seen a reversal of those allocations.

I think this would be better addressed by Dr. Tigner, who is going to be testifying later, and he will be making these decisions. Ours was just to advise him on which magnet to select. But I think he would emphasize the design that would be chosen.

Mr. **Barton**. OK. I guess another question that I have, and I would direct this to Mr. Rohrer, on the tunneling, the new tunneling technology. Do you feel that while they may not have had time to address the new technology that it is permissible to assume that there may be some advantages in the new technology that could significantly bring tunnel costs down?

Mr. **Rohrer**. I would say that if going through the process design, we don't try to improve, there would be effort made under either case. And as Professor Sciulli has said, those improvements would, as tunnel technology improves, would be implemented in either case. And how much that would be would be speculative a this time. But certainly every effort—any job that I've ever been connected with, if I were connected with the design and construction of the conventional facilities, I'd make every effort to reduce the cost.

And as you so well pointed out, the total cost of this projec really demands that we make every effort to reduce the cos whether it be the 107 mile or the 60 mile tunnel. The answer i yes, we would do that.

Mr. **Barton**. OK.

Mr. **Fuqua**. But, if the gentleman would yield——

Mr. **Barton**. Sure.

Mr. **Fuqua** [continuing]. This is not your basic conventional technology though in tunneling when you're talking about for the SSC There are certain requirements that it must have that normal tunneling, that you're doing for a subway or to transport water or fo other things, that this has to be very precise, waterproof, and a l of other factors that go into it.

Mr. **Rohrer.** Yes. Whereas a sewage tunnel, by the very fact of the hydrostatic pressure of the liquids flowing in it, you can have an entirely different seepage rate and infiltration or exfiltration, whichever the case would be, in a tunnel like that as compared to this. You have entirely different standards.

Mr. **Barton.** Again I'll address my question to Dr. Sciulli, but if you're not the proper person on the panel, let anybody answer. The statement is also made that the experience of the Fermilab, and the 1,000 magnets that have been built, is much more apropos to the cosine theta design. But again it's my understanding that the strength and the field strength of those magnets are much closer to the low-field design. So, one could argue that that experience would be more apropos to the low-field design.

Could you comment on that?

Dr. **Sciulli.** No, sir. The design of the Fermilab, they're a lower field than the magnets that are presently being discussed, the 6.4 Tesla. They are roughly 5 Tesla or a little below 5, between 4 and 5 Tesla.

The reason that the Fermilab magnets are lower was that that was the first magnet built in a production stage that was superconducting in a major machine, in a major high energy machine. And it underwent a lot of R&D to get those problems solved, the technical problems solved, to be able to construct those magnets.

Now, in the period since the Fermilab magnet was begun to be built in production, which is several years now, lots of things have happened. No. 1, in the process of doing that you really understood what the technical problems were in constructing the magnet, in keeping the superconductor superconducting.

The second thing that's happened is that—and people have engineered the magnets better. The second thing that's happened is that there has been a substantial part of the R&D, that we haven't discussed here, is substantial R&D that's going on on the superconducting material itself. And, in fact, that was the—this improvement in the superconducting material was the reason why the Central Design Group—and in fact the Panel agreed that the magnetic field assumed for the cosine theta magnet was raised from 6 to 6.4 Tesla.

The only problem, that is the engineering in the cosine theta magnets is engineered for 7 Tesla. They had been tested with a previous superconductor up to 6 Tesla and they had operated. With he new superconductor they've operated up to 6.5, 6.6 Tesla. And o, the superconductor has improved and it's continuing to improve n quality.

So, it's this, this is the other part of this R&D money that we're iscussing; the R&D that's going on in improving the cosine theta esign, both in the R&D program here and the SSC, but also in the &D program at HERA, the R&D program that has to do with the HIC magnets for a proposed facility at Brookhaven, plus the oper- tional experience of the cosine theta magnets at the Fermilab.

They are cosine theta magnets in the sense that they get their eld by placement of conductor without any help from iron. That , iron, as you know, transmits magnet fields rather easily. And so, y adding iron at low fields, you can improve, get more magnet eld for your current buck for the amount of current. But at high fields that doesn't work, and that's why a superferric magnet is in the range of 3 Tesla and below. But the cosine theta magnet is only limited by how well engineered the conductor is in its placement, and how well you hold it, and how much current you can pass through that conductor and still retain the superconducting quality.

Mr. **Barton**. Well, isn't it more difficult to hold that conductor in the high-field design than in the low-field design because of the added strength, the added forces involved?

Dr. **Sciulli**. Yes. The forces on the conductor are stronger for several reasons. One of them is that you're operating them at higher field. But those are problems that—where R&D has been used, and are generally perceived by the community to be solved.

In the case of the superferric magnet, there's a different set of problems. It's true that the forces are lower. But it turns out that in the evolution—I mean, I should go back. The superferric design, as talked about 2 years ago by Professor Wilson and Leon Lederman and others, was perceived to be a magnet somewhat like an ordinary iron magnet that people used before superconductivity that got some added boost from superconducting material. And when you got past the stage at which the iron saturated, somehow the shaping of the pole faces would give you a quality field that was still acceptable.

Now, what the TAC R&D has shown—because their designs show this—they were unable to do that with a single conductor. In fact, they have three conductors. There are three different conductors in the TAC design, whereas in the cosine theta design there is a single conductor. And those conductors are carrying, in some cases, twice as much current as you are in the cosine theta magnet.

Mr. **Barton**. But it's my understanding that the TAC people consider that an advantage in that it enables them to fine tune the current more closely to what they need. Now, I'm not a scientist, but——

Dr. **Sciulli**. Well, the Panel's position on this was that it was a complication of the design. It had lost its simplicity. And to many people who build technical systems, simplicity is less cost, complexity is higher cost. And it was the sense of the panel and its industrial consultants that this was a complication of the original concept, but obviously was a necessary one.

Mr. **Barton**. Mr. Chairman, I know we've got in this, and I could ask a number of questions, but you've given me permission to submit them for the record. I would just like to state that we've got a case here where honorable people have made a tough decision and a very close call. And you mentioned that nobody likes to lose but one especially doesn't like to lose when they think they played the game and have actually scored more points, but at the end of the game the referee makes a close judgment call and decides to award it to the other team. And obviously the TAC people are my people, and so I have to admire them for their design and to do everything possible to make sure that it's carefully considered.

I am a supporter of the SSC project. And if we ultimately end up with the high-field design, and if that is in fact the low-cost design and can be built, I'll be as strong a supporter as there is. But I do want the cost to really be closely looked at, and I know the chairman shares my concern, and I hope that we will do that in the near future.

Mr. FUQUA. Thank you. Mr. Packard.

Mr. PACKARD. In view of the time, Mr. Chairman, I'll preclude questions and defer to the final witness. We certainly want to hear from him.

Mr. FUQUA. Thank you, Mr. Packard. And we want to thank all of you for being with us this evening.

[Panel 2 questions and answers for the record follow:]

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COMMITTEE ON SCIENCE
AND TECHNOLOGY

ANSWERS TO QUESTIONS

from

THE HOUSE OF REPRESENTATIVES
SCIENCE AND TECHNOLOGY COMMITTEE

by

THE TEXAS ACCELERATOR CENTER

The following text is relevant to the hearings of October 29, 1985 and in response to the questions forwarded to us by Harlan Watson in a letter dated November 27, 1985. As an aid to answering some of the questions, we present table I.

TABLE I. The total funds at TAC are listed below. The Texas Accelerator Center came into being on March 9, 1984 and thus the first fiscal year is March 9, 1984 to September 30, 1984, there after October 1 to September 30. All funds in millions

	FY84 Actual	FY85 Actual	FY86 Contract	FY86 Proposals
DOE/Adv. Acc.				3.130
DOE/SSC	1.554	5.226	2.600	
Univs./SSC	1.542	.601	.400	
Univs./Other		.694	.782	
SDI/Grumman-SAIC			.283	.515
Baylor Medical			.300	1.000
DOD/Univ. Equip.				.182
TOTALS	3.096	6.521	4.365	4.827

The FY86 plan for the Texas Accelerator Center is to derive approximately one half of its funding from SSC work; one quarter from advanced linear accelerator work for high energy physics, SDI and industry; and one quarter for design and construction of a large NMR magnet for Baylor Medical Center. We already have 10 PhD students in this program and anticipate many more in the future.

1. What amounts of non-federal research funds does the Texas Accelerator Center receive?

1. University funds received by the Texas Accelerator Center come from Rice University, Texas A&M University, University of Houston, University of Texas, and The Houston Area Research Center a consortium of the four universities. The total funds received in FY84 and FY85 were $2.837 million and we expect $1.182 million for FY86. As indicated in table I, $2.543 million will go towards the SSC and $1.476 million on other R&D. The advanced accelerator R&D provides excellent problems for PhD students.

We have $.283 million from Grumman/SAIC to design future neutral particle beams for SDI and $.300 million from Baylor Medical Center to design a large superconducting NMR magnet. Both of these projects have follow-on proposals for construction. We also have a proposal submitted to DOD for rf equipment for our linac research.

How much funding did the Texas Accelerator Center receive from the Department of Energy or the SSC Central Design Group for its work on the superferric magnets? How much of its own funds did TAC provide for the superferric work?

2. The work on the SSC by the Texas Accelerator Center is ore general than just superferric magnets. We estimate that bout one half of the FY84 and FY85 funds were spent on uperferric magnets. We have contributed to many other aspects f the R&D program, including

- development of computer programs for tracking of particles in a collider,
- development of computer programs for calculations of magnetic fields,
- mechanical design techniques for cryostats,
- development and use of two additional companies to manufacture superconducting wire,
- development of a procedure for transferring superconducting magnet technology to industry. This procedure is now being used by CDG,
- development of a large helium refrigerator system for an accelerator,
- proof of efficiency of using long magnets,

- transfer of superferric magnet technology to three U.S. companies who have now built them.
- development of designs for clustering the SSC intersection regions to reduce cost and improve performance
- design of upgrade capability to provide for second-generation exploitation of the SSC
- development of the low-heat-loss cryogenic support now used in both magnet designs
- very large effort on accelerator design.

The DOE funds received by TAC for SSC R¢D were $6.78 million total in FY84 and FY85. We anticipate $2.6 million in FY86.

TAC put $2.143 million total in FY84 and 85 on the SSC and anticipate $.400 million in FY86.

3. What level of funding for FY 1986 is the Texas Accelerator Center requesting of either DOE or the SSC Central Design Group for its SSC activities, and what work will be performed?

3. The $2.6 million DOE and $.4 million university funds for FY86 SSC will provide for the following work;

- completion of superferric magnet full length work. It is extremely important to complete the tests of full length magnets constructed in industry. If the tests are successful, the companies will be certified by us as qualified superconducting magnet producers,
- design, construction and testing of correction magnets for the SSC. This required magnet system is nearly as large as the present Fermilab Tevatron.
- Design, construction and testing of a passive diode system for magnet-protection during operation.
- accelerator calculations.

4. What will be the disposition of the superferric magnets delivered by the General Dynamics Corporation?

4. The 3 - 28 meter magnets from General Dynamics Corporation in California, the 3 - 1 meter magnets from Intermagnetics General Corporation in New York and 1 - 1 meter magnet from Meyer Tool Incorporated in Illinois are nearly complete and will soon be tested. When these magnets pass all tests, we will certify these companies as capable of assembling accelerator quality superconducting magnets. The magnets at IGC and Meyer Tool are being constructed entirely at the companies' expense.

At that point, (spring 1986), the superferric design of the SSC will have been completed and proven and a detailed cost estimate will be available. The magnet technology will have been transferred to industry. Mass production of magnets could begin at any time thereafter.

5. Dr. McIntyre's testimony noted that "TAC does not agree with the CDG magnet decision." What were TAC's specific disagreements with the decision, and what are the technical bases for these disagreements?

5. The scientists at the Texas Accelerator Center do not agree with the CDG decision to choose the high field magnet style for the SSC. We submitted to the Department of Energy the technical basis of our disagreement. A copy of the document is attached. All review committees reported that either magnet style, low or high field, would work for the SSC, there was not a strong technical reason to choose one over the other. Therefore the important considerations should have been cost and physics.

a. We had proposed that some members of the selection panel be Nobel Laureates active in high energy physics. For example, Burton Richter, Samuel Ting, Carlo Rubbia, Sheldon Glashow, etc. (see attached letter), since physics must be a prime consideration. This proposal was rejected by the CDG.

b. The panel used the Fermilab Tevatron as the example of 1000 working high field magnets. The design field for the Fermilab Tevatron is 4.4 Tesla. It has only achieved 3.6 Tesla in the first two years of operation since the whole machine is limited by the weakest magnet of the 1000. The high field magnets have the characteristic of ''training'' which means that the first few times the magnet is cooled down and charged with current it does not reach design field. The high field design chosen by the CDG starts training below 5.5 Tesla, or about 80% of design field. Therefore we might expect the SSC as designed by the CDG to operate the first few years at 16 TeV not 20.

To assure a machine of 20 TeV, 5.5 Tesla instead of 6.4 should be used for the magnetic field. This would increase the cost of the high field collider by $340 million.

We note that the 3.6 Tesla field of the Tevatron is much closer to the 3 Tesla of the superferric design than to the 6.4 Tesla of the high field.

We also note that the chairman of the panel, Frank Sciulli, stated in his oral testimony that the field of the Tevatron was 5 Tesla. It is remarkable for the chairman of the panel not to know the field of the Tevatron when he used it as the example to prove the merit of the high field design.

Not one of the 15 superferric low field magnets we have constructed has trained. Every magnet has achieved full design field.

c. The high field magnet has serious problems with persistent currents. Persistent currents give both systematic and random errors to the magnetic field. We believe that this problem was not sufficiently addressed at the panel meeting. While a solution to the problem appears to be possible using thin-filament superconductor, no magnets have yet been made in this way, and the additional cost is not yet known.

The effects of persistent currents in the superferric low field magnet are negligible.

d. The panel report stated that the low field magnet was not simple. We have attached a drawing of the details of the two magnets. The two magnets are shown to the same scale. Both designs achieve exactly the same good-field aperture (hence performance). We submit that the low field magnet is very simple in comparison to the high field magnet. The high field magnet has 88 turns of superconducting cable compared to 10 in the low field. The superconducting cable in the high field magnet costs more than the whole low field magnet.

The forces in a magnet are proportional to the square of the magnetic field, thus the high field forces are about 5 times the low field. The present high field magnet has deformation occurring in the special stainless steel collars supporting the superconducting cable and must be redesigned.

The containment of the rectangular coils in the low field magnet is simple and there have been no problems in the 15 magnets tested.

e. The R¢D for the low field magnet would cost an additional $10 million to produce about 1% of the SSC magnets in industry and test them (see attached cost estimate from General Dynamics). The estimate for the high field is $50 million.

The tooling required for the high field magnet is very complicated compared to the low field. The high field coils must be wound on a special mandrel and then cured in a high pressure and temperature fixture. Tolerances are very difficult to achieve. It is this operation that the laboratories believe industry could not perform satisfactorily. This operation is not required for the low field superferric magnet.

This is the reason why the superferric magnets could be manufactured immediately in industry and the high field could only achieve industrial participation after two more years of R¢D.

f. Two of the members of the panel were the originators of the high field magnet design, Alvin Tollestrup of Fermilab and Bjorn Wiik of DESY. Alvin Tollestrup is actively involved in the present high field design. Without in any way impuning the integrity or credentials of these scientists, we believe that their presence on the panel brought its objectivity into question.

g. Since the low field magnets are being constructed in three different companies now and by the CDG schedule the high field magnets are two years away from being produced in industry; we cannot accept the opposite statement by Dr. Hulm, Dr. Dustman and Dr. Beuligmann. We can only assume they are misinformed.
It is true that Westinghouse and Grumman failed to produce successful magnets for ISABELLE, however those were high field magnets.

It is also true that in early December, 1985, the first industrially produced (Brown-Boveri) high field magnet for HERA was tested and was destroyed by electrical failure before achieving full field. Again this was a high-field design.

h. An overwhelming physics argument for the low field is the possibility of expansion to higher energy in the future by putting high field magnets in the same tunnel. In fact this advantage was stated by Dr. Rubbia in his testimony. Consideration of upgrade capability was ruled inappropriate to the magnet selection process. We believe this to be a tragic mistake.

i. The contingency used for the superferric magnets was 24.8% versus 21.5% for the high field. Since the superferric magnet has already been produced in industry and tested successfully versus a high field design which still has problems, e.g., persistent currents, collar deformation, no production in industry, no involvement of industry in sophisticated tooling, changing design, etc., we believe the contingency for the low field magnet should have been 10% or $75 million less.

j. As indicated in the attached drawing, the low field magnet is much smaller in cross-section. Thus the tunnel could be much smaller in cross-section. The CDG used a combination of 9 and 10 foot id. tunnels. We would use a 7 to 8 foot tunnel. The cost savings goes as the area of the tunnel and thus would reduce the low field tunnel costs by $250 million.

k. We believe the CDG has not been adequate in considering possible cost reductions. The cost of tunnel used by the CDG is $1350/ft ($930/ft direct + $150/ft EIDA + $270/ft contingency). There are 3 tunnels being constructed in Texas for $298/ft, $350/ft and $394/ft. We believe $700/ft is high, but even so that would have reduced the cost of the superferric design by $350 million.

From consideration of b, c, e, i, j, the tunnel and other simplifications we believe the superferric SSC design would be $1 billion less expensive than the high field. As evidence that scientists can disagree by large factors on the design and cost of accelerators we attach the article that appeared in the Fermilab News about the construction of Fermilab. Robert R. Wilson built Fermilab at twice the energy and less cost than was originally estimated.

TEXAS
ACCELERATOR CENTER

2319 Timberloch Place
The Woodlands, TX 77380
(713) 363-0121

November 1, 1985

MEMORANDUM

TO: Dr. William A. Wallenmeyer, Director
Division of High Energy Physics
U.S. Department of Energy
Washington, D.C. 19545

FROM: Dr. P.M. McIntyre and Dr. F.R. Huson
Texas Accelerator Center

SUBJECT: Technical Comments on the SSC Magnet Selection.

The Central Design Group has selected the Design D for preparation of an SSC construction proposal. TAC recognizes that a decision is necessary, and that DOE has vested the responsibility for managing the SSC R&D to the Central Design Group. We furthermore believe that both of the two competing designs, C and D, are viable and attractive choices for the SSC. TAC has already undertaken a strong role in the ongoing SSC effort under CDG leadership. First, TAC will complete its R&D on the superferric design during the first half of FY86. Second, TAC will undertake several major R&D tasks in developing the chosen high-field design and in preparing a construction proposal. These tasks include the design of the correction magnets that will be used to steer and correct beam motion in the SSC, the quench protection system used to protect the magnets from damage in the event of a quench, and super-computer studies of beam behavior in the SSC.

As honest scientists, however, we must express to you our disagreement with the CDG decision. The considerations that lead us to that disagreement are described below.

The Texas Accelerator Center developed the superferric design. The results of our development have established a number of attractive features of the superferric design:

1) It is efficient. The total superconductor required for the superferric design is one-fifth of that required for the high-field design. The total cold mass (structure that must be cooled to near absolute zero) is half as much. The heat load that must be cooled by special refrigerators is about 25% lower for the superferric design.

Operated by Houston Area Research Center, a research consortium of Rice University, Texas A&M University, The University of Texas at Austin and University of Houston

2) It is simple to build. There are one-half as many assembly steps required to fabricate a superferric magnet as are required to fabricate a high-field magnet. The coil for the superferric magnet consists of ten turns, compared to eighty turns for the high field design. The superferric coil is a simple rectangular coil, while the high-field coil must be wound on a cylindrical mandrel to extreme precision. The superferric coil does not require pressurized encapsulation in epoxy, while the high field coil does. All of these features combine to make a design that can be cheaply and reliably mass-produced.

3) It is reliable. TAC has built and tested 14 superferric magnets to date. Every magnet has achieved full design field with no quenches. Every magnet has produced a field quality which is acceptable for the SSC design requirements as determined by the Central Design Group.

4) It is inexpensive. Because of its simplicity and efficiency, the superferric design is inexpensive to build. According to the CDG cost estimates the total cost of superferric magnets for the SSC would be half that of the high-field design.

5) The superferric design uniquely can provide for future upgrade of the SSC. Every high energy collider to date has had a productive life of ≤ 10 years. It would be irresponsible to propose a multi-billion dollar facility without providing the possibility of such an upgrade if the physics results justify it. KEK/Hitachi recently successfully tested a superconducting dipole magnet to 9T field strength. With appropriate R&D during the next decade, it is plausible to assume that superconducting magnets with fields of 10-12 T can be ready for mass production by the end of the century. A double ring of these magnets could then be installed in the SSC tunnel, using the SSC as injector, and attain c.m energy of 130-160 TeV - another new generation of high energy physics. Such an upgrade could be realistically approached as an international collaboration.

In the Magnet Selection Advisory Panel report, the above attractive features of the superferric design were viewed to be offset by two considerations:

1) The superferric design requires a 100-mile tunnel circumference, while the high-field design requires a 60-mile circumference. The tunnel cost estimated by CDG was $1100/ft plus 30% contingency, or $1430/ft total. The additional tunnel cost using this estimate approximately cancels the cost savings on the magnet systems.

2) The successful operation of the Fermilab Tevatron was viewed as establishing a basis of confidence in high-field magnets. No similar base of experience exists for superferric magnets.

TAC disagrees with the decision of the CDG. We believe that the attractive features cited above make a compelling case for the superferric design. Regarding tunnel cost, data compiled by the DOE Construction Division show that tunnel cost can vary by a factor of three ($400-$1200/ft) according to the soil type, water conditions, and topography of the site. The CDG cost estimate assumes a cost at the high end of that range, in order to make it possible to build the SSC at any site in the United States. TAC assumes on the other hand that tunnel cost will be a significant parameter in the site selection process, so that a chosen site will likely have a tunnel cost near the low end of the range. The difference represents hundreds of millions of dollars and shifts the cost comparison accordingly.

Regarding the operational experience of the Tevatron as a basis of confidence in high-field designs, we point out that the Tevatron magnets operate at 3.6 Tesla field strength, closer to the superferric design field (3 Tesla) than to the high-field SSC design (6 Tesla). Persistent current fields present in the Tevatron magnets must be eliminated in the high-field design for the SSC. While there appears to be a technical solution to that problem by adopting recently developed fine-filament superconducting cable, no magnet has to date been built with this cable, and the cost of the high-field design will be increased by an amount still to be determined. Lastly, the magnetic forces on the Tevatron magnets are half the forces on the high-field SSC design, and the heat load is ten times greater. All of these considerations qualify considerably the degree to which Tevatron experience can be viewed as a basis of confidence in selecting the high-field design.

Scientists can honestly disagree on important issues. It sometimes occurs that the right course will become clear only as events develop. It is instructive in this light to recall the events that led to the building of Fermilab. In the 1960's, when Fermilab was being specified, accelerator experts at the Radiation Laboratory in Berkeley made a detailed design of a 200 GeV accelerator with an estimated cost of $350M. A lone outsider, Robert R. Wilson, kept saying he could build a much less expensive accelerator. The AEC chose to put the accelerator in Illinois and put an upper limit on its cost of $240M. As we all know Wilson built a 400 GeV (twice the energy) accelerator for $235M. Perhaps in the same tradition, TAC believes that the SSC can be built for a total cost of less than $ billion.

PMM/la

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April 24, 1985

SSC
University of California
Lawrence Berkeley Laboratory
One Cyclotron Rd
Mail Station 90-4040
Berkeley, CA 94720

Attn: Maury Tigner

RE: Letter of April 12, 1985, Magnet Selection

Dear Maury,

I have five general comments relative to the magnet selection process. They are as follows:

I. Time for Selection

The situation at the Texas Accelerator Center is that we are in the process of making measurements of magnet models and trying to understand the measurements. This is a normal process that takes several months to obtain data that one can really believe, particularly to the accuracy of 1 in 10^4. We are also in the process of making many models, the order of a dozen, so that we can have a good estimate of the random errors expected in these magnets. The completion of these dozen models will not be made until the end of summer. General Dynamics Corporation is in the process of assembling three 28 meter magnets, the first of which will arrive at the Texas Accelerator Center in September, the next one October and the last one in November.

The High Field Magnet Design is really just getting underway. The Model D as I understand it, has 1 one-meter magnet model at this time, which has not really been measured for magnetic quality. Questions of clamping the coils so there is no movement, training and magnetic measurement errors will certainly not be understood with this High Field Magnet until Fall. It is clear that Magnet Design D is not as far along at this point as Magnet Design A was at the time of the reference design. The question of persistant current is certainly not settled in the High Field Magnet.

My conclusion of the above analysis is that the magnet selection should start in late fall or early winter and be complete by the end of December, then the decision will be based on many models of both types of magnets and many measurements.

II. Tunnel Costs

From the data I collected for my seminar at Harvard on April 17, I found that the reference design studies Tunnel Costs were an upper limit in cost, and that the Tunnel Cost depends on the type and size of the magnet. I find that the tunnel cost is proportional to a constant for fixed things around the accelerator plus another term times the circumference. The conctant on the second term is proportional to the cross-sectional area of the tunnel. A two-in-one design versus a one-in-one design will in most cases take less space in a tunnel, this could reduce the tunnel cost by as much as 20 percent. Since the total tunnel cost is about 1/3 of the total cost of the SSC facility this is a very large effect and should be included in the total cost estimation for a given type of magnet design.

In preparing the seminar for Harvard I also found in the data collected by Texas A&M that in most cases a bi-planer tunnel with a bend in the center of less than 1° could save as much as 20 percent over a single-plane tunnel. In most sights that I have looked at personally which includes Fermilab, Colorado, and Texas it usually turns out that there is a low spot bisecting the circle, and thus a bi-planer fit to the topology is appropriate.

I realize that the reference design study cost estimate was based on a hypothetical sight with various types of geology and therefore various types of construction for the tunnel. I would therefore feel that it would be appropriate at this stage of the cost estimating to at least state that the reference design study was an upperlimit of the cost and that the cost of the tunnel may range to as low as 1/2 of that cost. This makes a tremendous difference in the total cost of the SSC, e.g. for Design C this could reduce the total cost by $500,000.00.

I will work with Jim Sanford and Tim Toohig to try to obtain agreement on the comparison of the cost of various tunnels, e.g. Lep, main ring, Tristan, deep tunnels in Chicago, and tunneling in Texas, with the reference design study cost.

III. Selection Advisory Panel

Many aspects effect the magnetic field choice for the SSC e.g. the accelerator performance, reliability, construction time, flexibility for future Physics, total cost of the facility, etc. It appears from the various task forces that have been meeting during the year, that no particular magnetic field is technically favored. Therefore the decision of the magnetic field will be based on more subjective criterion. I applaud your choice of panel members to be distinguished scientists, engineers, and industrialists, however, I do believe that the most important aspect in making the selection should be based on physics. We all recall that very few High Energy Physics accelerators have ended up doing the type of physics for which they were built, and therefore maximum flexibility for the future must be incorportated into the construction of the facility. I propose that we pick our best possible scientists to make this selection. I would recommend the most active Nobel Laureates, e.g. B. Richter, J. Cronin, S. Ting, C. Rubbia, and S. Glashow.

IV. Reference to Special Problems

In your charge to the magnet type selection advisory panel you gave particular reference to them to look for impacts such as lengthened construction time for a larger radius or for special portals or on site factory facilities to take care of particular magnet requirements. I would like to add to that particular consideration the time scale for magnet construction. The Superferric 3 Tesla magnets can be constructed in a 2 year time scale versus 5 years for the High Field Magnets. This could be one of the largest impacts on the completion of the SSC facility on a rapid schedule.

V. Imput Data to the Magnet Type Selection Advisory Panel

I would hope that each magnet designer would be ask to present his data to the panel and to have open discussion with them on the various advantages and disadvantages of their design.

Sincerely,

Russ

Dr. F. R. Huson

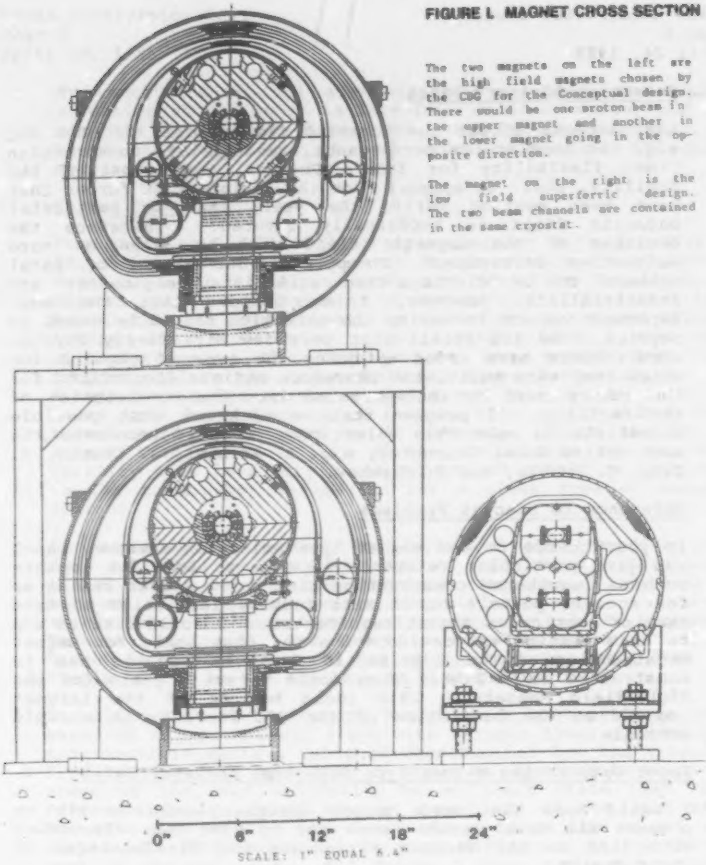

FIGURE I. MAGNET CROSS SECTION

The two magnets on the left are the high field magnets chosen by the CBG for the Conceptual design. There would be one proton beam in the upper magnet and another in the lower magnet going in the opposite direction.

The magnet on the right is the low field superferric design. The two beam channels are contained in the same cryostat.

R. Huson
[illegible]

GENERAL DYNAMICS
Convair Division
Kearny Mesa Plant, P.O. Box 85357, San Diego, California 92138 • Lindbergh Field Plant, P.O. Box 85377, San Diego, California 92138
Procurement P.O. Box 80827 • Accounting P.O. Box 85318
619 573-8000

RECEIVED

110-2-85-291
JGL:jw
23 August 1985

Houston Area Research Center
2202 Timberloch Place, Suite 200
The Woodlands, Texas 77380

Attention: Anne Sherman

Subject: Twelve 35 Meter Magnets

Reference: (a) TAC letter dated 18 July 1985
(b) Meeting, J. G. Lemmo, E. Kimmy (General Dynamics)/D. Davis, A. Sherman (HARC)/B. C. Huguelet, R. Huson (TAC) 7 August 1985

Gentlemen:

In response to Reference (a), General Dynamics considers $1,900,000 a reasonable budgetary planning amount for the fabrication of 12 thirty-five meter magnets to the current design. As agreed during Reference (b), we base this budgetary planning estimate on the understanding that the contract for the task will be Cost-Plus-Fixed-Fee in lieu of Fixed-Price. Additionally, the following assumptions were considered in developing our estimate:

1. Contract task will begin 1 December 1985 with complete delivery before 31 December 1986.
2. All materials will be provided by HARC on-dock General Dynamics when required and ready-to-use.
3. Current tooling will be modified and used by General Dynamics.
4. Functional testing by General Dynamics is not included in our budgetary planning amount.
5. Shipment to TAC by truck is included.
6. This task is to fabricate to TAC design/engineering, and the complete TAC design/engineering package will be provided to General Dynamics at time of contract.
7. Fee is included at 10% of cost.

GENERAL DYNAMICS
Convair Division

110-2-85-291
23 August 1985
Page Two

General Dynamics Corporation is in the process of realigning Convair into two divisions. Those elements of the division responsible for ballistic missiles and space programs, including magnet programs, will form the new Space Systems Division. Dr. Alan M. Lovelace has been appointed Vice President and General Manager of this new division. The Convair Division, headed by M John E. McSweeny, will continue to be responsible for Cruise Missile program and product development and related advanced missile systems. Establishment of these two divisions was promp by our desire to provide maximum support for the future space an defense needs of the nation.

Pursuant to this realignment, the Space Systems Division, under leadership of Dr. Lovelace and his staff, has total management responsibility for the TAC Magnet Program.

If you have any questions, please call either Mike Kimmy (619) 692-4715 or Joe Lemmo (619) 547-5877.

Thank you for your continued confidence in General Dynamics to support you in this important national program.

J. G. Lemmo
Contract Negotiator

cc: B. C. Huguelet
R. Huson
Texas Accelerator Center
2319 Timberloch Place (Bay H)
The Woodlands, TX 77380

fermilab report
Fermi National Accelerator Laboratory Monthly Report
February 1983

The following is an excerpt from a paper published by Lillian Hoddeson, Historian of Modern Physics at Fermilab, in Social Studies of Science, Vol. 13, No.1 (1983), published by Sage Publication, London and Beverly Hills. It is reprinted with permission of the author and the publisher.

THE ESTABLISHMENT OF FERMILAB

Lillian Hoddeson

In 1959 all operating machines were producing relatively low intensity beams, and it was believed that one had to choose between high intensity and high energy. For not until August 1960 would the CERN Proton Synchrotron (CPS), after operating for eight months, demonstrate (to almost everyone's surprise) that AG-focusing synchrotrons could produce both high energies and remarkably high intensities, of the order of 10^{11} protons per second.

Several proposals for high intensity machines were made in the U. S. One came from an innovative group of physicists from various midwest universities called the Midwestern Universities Research Associatioin (MURA). This group, led by Donald Kerst of the University of Illinois, had formed soon after the Brookhaven Cosmotron was completed in 1952. MURA hoped to design the next large U. S. accelerator facility, which reasonably, they felt, should be located in their part of the country. The concept of a 'fixed-field alternating-gradient accelerator' (FFAG), which would produce an intense proton beam with an energy of approximately 300 GeV, achieved by colliding 10-15 GeV beams, was conceived of first at MURA in the summer of 1954 by Keith Symon, and independently by Snyder, A. A. Kolomensky, L. H. Thomas, and Ohkawa of Miyamoto's laboratory. It was developed further in 1955 by several members of the MURA group.

In the summer of 1959 the MURA group held a study-conference in Madison, Wisconsin, aimed at generating support for MURA and reconsidering the FFAG design in relation to all the existing chemes of achieving high energy or high intensity. The concep- al root of both the Fermilab and KEK accelerators grew out of he discussions at this meeting. It was generally felt then that e only practical way to produce energies in the several hundred y range was by colliding accelerated beams. Furthermore, it s believed that fixed target machines of very high energy would exorbitantly expensive (if even feasible technically)--and rhaps not useful for physics anyway, because above proximately 5 GeV all the existing schemes for identifying rticles were suspect. (The fear was that all particles would k alike, being confined to a narrow forward-moving cone.)

During the meeting, Matthew Sands, an iconoclastic partici- t from the California Institute of Technology (Caltech), became challenged by the problem of designing a reasonable cost fixed target machine aimed at approximately 300 GeV. He reinvented the concept, suggested several years earlier by Wilson and others (including F. Heyn and Lee Teng), of forming a cascade of accelerators, injecting an accelerated beam from one machine into another. By first accelerating the particles up to a high energy in a 'booster' synchrotron and then, with a reasonably high injection field, feeding the beam into a main synchrotron, Sands hoped to avoid the use of very large (and therefore very costly) magnets in the highest energy machine. Although it was thought then that one could not control such a large system or use magnets as small as Sands specified, working out details with a subgroup of the MURA study (which included Courant and M. Hildred Blewett from Brookhaven, and Alvin Tollestrup from Caltech), Sands showed mathematically that the magnet aperture in the mai ring could be but a few square centimeters in size. Optimizatio of parameters gave the result that to achieve 300 GeV most efficiently one should inject from a 10 GeV range 'rapid cycling', o 'high repetition rate' (HR) 'booster', synchrotron into the mai ring. The high repetition rate of such a booster would enable high intensity to be achieved.

Fermilab's pre-history begins at this point. Most of th participants at the MURA summer study did not take the Sands proposal seriously. However, Sands and Tollestrup continued to wor on the idea after returning to Caltech, also involving their colleague Robert Walker in the project. They convinced Caltech support a study during the following summer to complete the design. Those invited included Snyder, Courant, M. H. Blewett fr Brookhaven, Kenneth Robinson from the Cambridge Electr Accelerator, and Robert Hulsizer from the University of Illinoi

Since Caltech judged building the machine Sands had desig to be too large a project for them to support alone, a sponsori group formed called the Western Accelerator Group (WAG), whi included physicists from Caltech, the University of California both Los Angeles and San Diego, and the University of Southe California. Berkeley declined the offer to join WAG, for in late '50's, researchers there (for instance, David Judd and Ll Smith) had been working on their own concept for a very h energy machine based on a proposal of Christofilos. In Ap 1961, WAG submitted its proposal to the AEC.

One of those who appreciated WAG's design was Wilson, wh earlier suggestion of cascade injection had stimulated the Sa design. Several years later Wilson would build Fermilab on model. Presciently, Wilson wrote to Sands on 25 April 1961: have been watching your efforts with the 300 GeV machine open-mouthed admiration. It seems to me that you are workin the right problem and at the right time, and I am sure something will come of it all.'

Meanwhile, interest in a several hundred GeV machine mounting in other parts of the U. S. Ten months earlier

August 1960. Wilson had organized an unofficial conference in Rochester, NY, at which approximately thirty physicists who were attending the concurrent Rochester Conference on High Energy Physics, took part in 'intensive discussion of. . .the desirability of super energy from the point of the theory of particles. . .[and] the experimental practibility of constructing and using ultrahigh energy machines.' Wilson summarized:

> It was generally agreed that for, say, 100 million dollars--or at most 200 million--it would be feasible to push the design of a conventional alternating gradient proton synchrotron to 100 GeV or even higher and that this might also cover the first round of experiments. With the same reasoning, but pushing the kind of tolerances that must be held, we could even think of attaining 1000 GeV and at a cost of less than one billion dollars--really a bargain of course.

Further support for such projections came at a meeting in September 1960 at the American Institute of Physics in New York (attended by five leading Russian physicists, including Veksler and N. Bogoliubov), and at the 1961 International Particle Accelerator Conference at Brookhaven (attended by Kitagaki, Nishikawa, Shigeki Suwa, and Kobayashi), at which the most recent machine concepts were discussed. In February 1962, Brookhaven submitted a proposal to the AEC for a 300-1000 GeV design study. In February and December of 1962, Berkeley submitted proposals for study of machines in the 100-300 GeV range. WAG's proposal for a 300 GeV machine was now in serious competition with proposals from the established accelerator laboratories.

The AEC, having at the same time to evaluate proposals for other large machines, including one by Cornell to upgrade its machine and one by MURA to build a 10 GeV FFAG, found itself in need of advice. For the first time in America there was too little funding available to support all the accelerator proposals. From this point on, high energy physicists would be spending more and more time on panels, both with other physicists, and with members of the government, to discuss funding. Extensive participation by the U. S. Congress had already begun with hearings in 1959-60 over the issue of supporting Stanford's linear accelerator, the first machine with a budget in the 100 million dollar range.

Most influential of the American accelerator panels in this period was that headed by Norman Ramsey during 1962 and 1963. After extended discussion, this panel ranked the proposals and, n a report in April 1963, suggested thirteen steps to be taken n order. The first was that Berkeley, rather than Brookhaven or altech, construct a proton accelerator of approximately 200 GeV; his was the machine tnat eventually became Fermilab. The next hree steps were: that Brookhaven construct storage rings 'after suitable study'; that design studies be conducted at Brookhaven or a 600-1000 GeV national accelerator; and that MURA in fiscal ear 1965 construct 'a super-current accelerator without permitting this to delay the steps toward high energy. . . .' WAG's proposal was not mentioned. Brookhaven and Berkeley were favored for the very high energy machines because they were the most experienced accelerator laboratories. Ranking the MURA machine fourth effectively phased it out; this move would later enter into the selection of Fermilab's site.

Two other features of the Ramsey panel's report are notable. First, the recommendation emphasized that studies for new high energy facilities 'should be permitted to proceed to greater detail with explicit authorization so that ideas can be explored conclusively without implying any commitment to proceed.' Thus accelerator development advanced officially into the era of the 'design study,' in which groups of physicists are authorized to prepare detailed designs over a period of several years, without any commitment to build. Secondly, the panel stressed that future high energy laboratories be nationwide rather than regional facilities, having a strong users' representation as well as in-house research staff.

An informal but influential paper, prepared in June 1963 by Fermilab's present director Leon Lederman, then participating in the committee headed by M. L. Good appointed to review the Ramsey panel's report, defined the concept of the 'Truly National Laboratory', or TNL--a laboratory whose ultimate governing body, to which even the director would be responsible, is a nationally represented committee, and whose users' group is 'at home and loved'. Not only, Lederman argued, should users have the right of access to the machine, ancillary equipment and any specialized services that are offered, but also (1) laboratory and office space on site; (2) a 'substantial' support budget to supplement their own grants; (3) strong representation on the scheduling committee; and (4) an active users' advisory committee. He suggested that the site be selected with a view towards 'ease in airport-to-site transportation, housing, and school facilities and general pleasantness'. This concept would be put into operation four years later in the design of Fermilab.

After the Good Committee endorsed the Ramsey panel's recommendations, the AEC appropriated money for Berkeley to conduct, under the direction of Edward Lofgren, a detailed study to design a 200 GeV accelerator. And two years later, in June 1965, the design study appeared, described in two thick blue books a four accelerator cascade as in the Sands proposal, but differing substantially from Sands' concept in technical features, most notably in its size. In the Berkeley design, the magnet apertures were comparatively huge, resulting in a budget of over 340 million dollars.

It was a poor time for Berkeley to present such an expensive proposal, for Congress was just then beginning to feel that high energy physics was oversupported, and that too large a proportion of funds was going to California. Furthermore, non-Berkeley physicists were complaining that in the past they had not been granted enough time on Berkeley's machines. In this context, in the fall and winter of 1965, Wilson dramatically entered the story of the 200 GeV accelerator. He had had an opportunity during the previous summer to study the Berkeley design, as presented by McMillan at a meeting in Frascati, Italy. Feeling strongly that the Berkeley design was too conservative, and thus too expensive, Wilson wrote a series of critical papers. By December, he had drawn up an alternative proposal for a 200 GeV machine at a cost of only 50 million dollars, estimating only 100 million dollars to achieve 600 to 1000 GeV. He based his estimates on economizing features used in the Cornell electron synchrotron--for example, small magnets and austere experimental facilities. Another alternative, suggested by Samuel Devons of Columbia University, was to add a further level of acceleration to the Brookhaven machine, using the AGS as injector. While the Berkeley physicists tended to dismiss the economizing suggestions of both Wilson and Devons, the AEC did not, and announced a cost ceiling of 240 million dollars, so that Berkeley had to prepare a 'reduced scope' design.

The debates in 1965 further focused on the location of the new laboratory. While Berkeley had assumed throughout that the site would be in California, physicists and politicians in other states actively began to question this assumption. In April 1965, after receiving Colorado's independent site proposal, the AEC began to advertise for other proposals. One hundred and twenty-five were received, suggesting over 200 sites, with one or more from each of 46 states. By September 1965, the AEC had reduced the number of proposals to 85, and in March 1966, with the help of a National Academy of Sciences site evaluation committee headed by Emanuel Piore of IBM, only six remained.

The final choice of Weston, Illinois, about 30 miles west of the centre of Chicago, was made in December 1966. It is rumoured to have been the result of political agreements through which Lyndon Johnson repaid a debt to the midwest incurred by the closing down of MURA in 1965, at the same time obligating the Illinois senator Everett Dirkson to support Civil Rights legislation.

Meanwhile, Frederick Seitz, President of the National Academy of Sciences, took the initiative of organizing a national university-supported organization, modeled after Brookhaven's AUI, and named the Universities Research Association (URA), to ouild and operate the new accelerator laboratory. In June 1965, he URA consortium, composed originally of 34, and later of over 0, universities broadly distributed throughout the United tates, was incorporated. Ramsey was selected as its President.

The URA's first job was to choose a director for the new aboratory. It was initially intended to have the position divid into a physics and an accelerator director. The first offer, at of accelerator director, went to Lofgren, who had been head the Berkeley design project. But Lofgren, apparently supporting Berkeley's hope that the laboratory be in California, turned the offer down on the grounds that the Illinois site was unsuitable and the 240 million dollar budget impossibly low. Then on 6 February 1967, the URA formally offered Wilson the combined position of accelerator and laboratory director. Wilson accepted on 1 March 1967.

Wilson spent the remainder of the academic year 1966-67, operating from his home base in Cornell, on staffing, designing, planning conferences, and arranging for an engineering firm to take on the construction. Staffing was somewhat hindered by the fact that the Illinois site--6800 acres of totally flat cornfield--was quite unappealing as a place to live; summers were hot and humid, winters cold and icy, and there were no nearby mountains or ocean. Staffing was aided, however, by the fact that MURA and the Cambridge Electron Accelerator were then both at the point of closing down.

Throughout the summer of 1967, Wilson held workshops to design the laboratory. To emphasize his intention to make the facility 'truly national', as discussed by Lederman, he named it 'The National Accelerator Laboratory', NAL. Since Illinois was having local difficulties buying the land that was to be turned over to the Federal government, the new laboratory was not able to move to Weston until fall 1968. The design workshops, attended on the average by 25 participants from various parts of the U. S., supported by their home institutions, were therefore held in temporary offices in Oak Brook, a suburb of Chicago. The conferees played important roles in choosing basic parameters, such as the radius of the main synchrotron ring, and deciding where on the site to place particular components. The workshops also gave Wilson and the conferees a chance to look each other over as potential staff and boss. Indeed, at the end of the summer, approximately half those attending the workshop joined Wilson's staff.

The design report for NAL, completed during the fall of 1967 and issued in January 1968, described a cascade machine quite similar to that proposed by Sands in 1959, but with some features of the Berkeley design. Many innovations reduced costs: small 'H design' magnets with minimal enclosures and a relatively small main-ring tunnel, separated-function magnets for bending and focusing in the main ring, modular equipment in the main ring, a single emergent beam split after extraction, newly developed solid state rectifiers (instead of traditional flywheel generators) tying the magnets directly to AC power lines, an electrostatic septum invented by Alfred Maschke, a main ring tunnel built directly on glacial clay, and simple stands rather than expensive girder supports for the magnets. The design also included a built-in option to go later to 400 GeV. By mid-April, Congress had passed and Johnson had signed the bill authorizing the project at 250 million dollars.

Only the linac group was working at Weston in 1967-68. The rest of the staff moved there in October 1968. Then a frantic three-year period of actual construction began in December 1968 with the linac groundbreaking. The emphasis was constantly on economy and speed; Wilson and his Deputy Director, Edwin Goldwasser, both kept setting tight schedules and trying to motivate the staff to beat them in order to save labour costs. Experimental facilities (including a meson area, a neutrino area, and a proton area) were planned by a national group at summer studies held in 1968 and 1969 in Aspen, Colorado, and in 1970 at NAL. The first 200 GeV beam passed through the main ring in March 1972; later, the energy rose to 500 GeV and will soon, through the addition of a superconducting second ring in the main tunnel, increase to 1000 GeV. In May 1974, NAL was renamed Fermi National Accelerator, or Fermilab for short, in honour of Enrico Fermi.

READEX FICHE

6. Dr. McIntyre noted that superferric magnets appear to be an ideal choice for compact, low-cost synchrotron sources for microcircuit lithography. How would their cost and performance compare with larger devices, such as the Stanford Synchrotron Radiation Laboratory or the National Synchrotron Light Source?

6. Synchrotron radiation is a very promising source of intense short wavelength light for science and technology. Electron storage rings in the energy range .5-1 GeV produce copious light in the spectrum from ultraviolet to near X-rays. There are now several excellent national facilities operating in the United States - NSLS, SLAC, CHESS, ALADIN. These facilities serve the needs of a broad and exciting research program.

Synchrotron radiation is of great interest in the development of ever higher device density for microcircuits. Several major microcircuit manufacturers have approached TAC about the development of a compact, dedicated synchrotron light source for microcircuit development and fabrication. While the national facilities serve a valuable and productive R¢D role, it appears that each manufacturer wishes to obtain a dedicated light source which would be installed and operated in-plant for device development and fabrication. Development of sources for this purpose is under way in Germany and Japan.

TAC has developed design concepts for a synchrotron light source. Our superferric magnet technology appears to be an attractive choice for the purpose. Separate accelerator and storage rings should enable us to overcome some of the performance limitations encountered in recent U.S. facilities. While our design efforts are at this state preliminary, we are very encouraged about the possibility of developing and producing a compact, high-performance light source that can be marketed to the U.S. microcircuit industry.

7. Dr. McIntyre mentioned that civil engineers at your universities have invented a new tunneling technology that promises to significantly increase tunneling rates and reduce costs. Please expand on that technology.

(a) What rates of advance were achieved?

(b) On what types of soil were these rates of advance based?

(c) Since the SSC tunnel would extend over a wide area and probably be constructed in soils and geologic strata which vary considerably, what "average" rate of advance might realistically be achieved?

(d) What laboratory experiments were conducted to verify that such a rate was feasible and how did it take into account variations in moisture content and the impact water could have on tunnel flooding?

(e) Would the concrete liner for such a tunnel cure at the same rate as tunneling advance?

7. Professor Louis Thompson of Texas A¢M University has answered this question. It is attached.

TEXAS
ACCELERATOR CENTER

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TUNNELS

by

Louis Thompson
Texas A&M University

The Superconducting Super Collider (SSC) will be the most magnificent scientific device ever built by man, but because there has been so little effective research in tunnel construction, it will be built in tunnels using a technology that has changed little since civil war time. In fact if inflation is considered it may be that the cost of tunnels has increased in the last 120 years. Also the time required to construct tunnels has increased in the last 120 years. One hundred years ago it took about 9 years to build a 10 mile long tunnel through the Alps. Several years ago a parallel tunnel was constructed in about 10 years. During this time dynamite was invented by Nobel in 1867 and tunnel boring machines (TBM) were first used in Italy in 1846. Railroads were first used in tunnels around 1865. The first practical TBM was used in this country in 1953. In many cases the rate the material could be excavated increased but the rate the muck could be removed from the tunnel did not. Today the very efficient TBM can cut 12 to 15 inches per minute in soft limestone and shale but seldom makes more than 150 ft per day headway because most of time is spent waiting for the return of muck trains, waiting extension of tracks and utilities and waiting for installation of temporary supports. Tunnel cost will be reduced when the TBM can be kept operating and the rate of advance thus increased. The problems to be solved are in circulation not in devising new ways to excavate faster.

Since it is estimated that the cost of the SSC tunnel will be a third of the total cost of the SSC project, a serious study should be made to determine the way to build the lowest cost tunnel.

The cost of a tunnel is controlled by seven major factors. The first factor is the state of the Art of tunnel technology available to the constructor. The second factor is the user requirements necessary for operation such as length, depth, height, width, etc. The third factor is the economic conditions at time of bid letting which influence the number of bidders and their profit and overhead margin. The fourth factor is the type of ground the tunnel must penetrate. The fifth factor is the geographic location of the project. The sixth factor is the engineering design of the project. The seventh and last major factor is the kind of contract used.

The first factor - Construction technology - cannot readily influence contractor bids unless contractors see the new methods in use. They need demonstrations to convince them, much the same as farmers need demonstrations before they will try anything new. In fact as long as contractors can get jobs, they really are not interested in anything new that will lower costs.

The second and third factors - owner requirements and economic conditions are not controllable by the principals of the SSC project (managers, planners, engineers, contractors, etc.)

The last four factors, type of ground, geographic location, engineering design and contracts can be controlled by systems to determine the way to build the lowest cost tunnel.

The computer code COSTUN was designed 15 years ago to do just this. It was based on 15 years of data. It considers all of the major factors except contract type. It is an engineers tool to compare methods, sites, ground type and conditions, and different designs. It is believed to give results within 25%. However there are no federal or state data bases so that costs and necessary data can be retrieved and large improvements made. When checked against the 3 - eight foot diameter concrete Austin Texas tunnels which cost about $300 per foot and were bored at a rate of 160 ft./day it gave results that were exactly the 2nd high bidder.

The attached proposal describes the various methods to improve tunnelling. (See Appendix II.)

COST DATA FOR AUSTIN TEXAS TUNNEL CONTRACTS

8-9-85

L. J. Thompson
Civil Engineering Dept.
Texas A&M University
College Station, TX

Project	Upper Onion Creek Project	Lower Onion Creek Project	Johnson Creek Project
Type	Sanitary Sewer	Sanitary Sewer	Storm Sewer
Contractor	7-K Cont. Co. (Kenny)	Mole Const. Co. (S&M)	SYRO Steel Co.
Home Office	Chicago	Cleveland, Ohio	Salt Lake City, UT
Inside Dia.	84 inches	84 inches	96 inches
Cut Dia.	110 inches	104 - 110 inches	118 inches
Conc. lining thickness	8 inches	8 inches	8 inches
Type lining	Cast-in-place	Cast in Place	Precast segments
Grout thickness	2 inches	1 inch	3 inches
Temp. Supports	Ribs & Lagging 3 inches	Plywood 1 inch Ribs & Lagging 4 inches	None
Type of Ground	Chalk Tuff Limestone Claystone	Claystone Siltstone	Limestone
Cost per foot	$325-350	293	$245+$120=$365 $120 in for mobilization prorated over over 8700 ft.
Length (ft)	20,500	29,600	8,700

Columbia University
DEPARTMENT OF PHYSICS

NEVIS LABORATORIES
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December 19, 1985

Congressman Don Fuqua
Chairman, Committee on Science
and Technology
U. S. House of Representatives
Suite 2321 Rayburn House Office Bldg.
Washington, DC 20515

Dear Congressman Fuqua:

I am enclosing my responses to the questions sent to me from your Subcommittee. As I mentioned in my telephone conversation with your staff, I was out of the country much of the past few weeks. I regret that the answers reach you late.

If there is any more that I can do, please do not hesitate to let me know.

Sincerely,

Frank Sciulli

Frank Sciulli
Professor of Physics;
Panel Chairman, SSC
Magnet Selection

encls.

1. What were the cost estimates of the superferric magnets and cosine-theta magnets, and how were these estimates developed? Specifically, what is the basis for the (a) development costs, (b) fabrication costs, (c) installation costs, (d) testing costs, and (e) maintenance costs for each?

The cost estimates for superferric and cosine θ magnets were developed (i.e. detailed 'bottoms-up' cost estimates) independently by DOE laboratories and by two industrial firms. Five magnet types (three cosine θ and two superferric) were estimated. The results were compiled in the SSC Report SSC-SR-1012 entitled, "Cost Comparisons for SSC Magnet Dependent Systems". The institutions that developed the costs for the various magnet types are listed below. As shown in the Table, three independent cost estimates were provided for both magnet types C and D.

Table: Cost Estimators for SSC Magnet Styles

Magnet Style	Cosine θ			Superferric	
Magnet Type	A	B	D	C	C*
(1)	BNL & LBL	FNAL	BNL & LBL & FNAL	TAC	TAC
(2)			General Dynamics Corp.	General Dynamics Corp.	
(3)			Westinghouse Corp.	Westinghouse Corp.	

All magnet costs estimates were reviewed by the CDG Project Planning Group for completeness, uniformity in method, and accuracy. These costs were then reviewed by a Cost Estimating Task Force appointed by the CDG Director. Subsequently the costs were reviewed by the Magnet Selection Advisory Panel prior to the selection of a magnet style for the SSC.

1. (continued)

The magnet cost estimates included costs for fabrication, installation, and testing. Development costs and maintenance costs were not included as a part of the construction cost estimates.

2. How were the magnet cost estimates verified? By labor and material records from prototype magnets? By peer review?

The magnet costs estimates were verified by having the estimates developed by three independent qualified groups which included DOE laboratories and industrial firms.

Up-to-date materials costs were obtained by direct quotes from qualified vendors and manufacturers or else by recent actual experience with purchases of similar items. Labor costs were based upon the experience of the laboratory (or the industrial estimator) in the fabrication of previous superconducting magnet systems or similar technical systems.

Additional verification was by peer review which included the following groups:

- the CDG Project Planning Group ,
- the Cost Estimating Task Force ,
- the Magnet Selection Advisory Panel .

It should be noted that the methods and procedures used for cost estimating were similar to those used for the SSC Reference Design Study (RDS) of 1984. The magnet cost estimates of the RDS were reviewed by RDS Technical Advisory Groups, DOE, DOE Advisory Groups, and the DOE Independent Costs Estimating Group (ICE).

3. You noted that the cosine-theta version with two beams per cryostat was rejected due to commissioning and operating complication. Please expand on what you meant by this.

The Report of the Task Force on SSC Commission and Operations (SSC-SR-1005) concluded, ..."With magnet systems which are coupled either cryogenically (i.e. two beams per cryostat) or magnetically (same magnetic flux through both rings), both machines are off-line and require more downtime for magnet replacement when a magnet fails. Coupled systems are therefore less flexible in terms of initial installation, survey and subsequent alignment, commissioning, accelerator physics studies, return to service after a magnet replacement, and flexibility for subsequent physics programs. Also, the possibility of adding redundancy in the cryogenic system is enhanced by the one-in-one solution." This Task Force examined critically issues related to injection, beam abort, and acceleration during commissioning, accelerator studies, and particle physics operation.

The Magnet Selection Advisory Panel, after reviewing the question, agreed with these conclusions, believing that such comparisons invariably favor rings that have the least coupling, whether cryogenic, magnetic, or spatial. As a partial list of such advantages for the one-in-one design, we list:

(a) Beam commissioning or power supply studies can be continued on one ring while the other ring is being repaired.

(b) Accelerator studies will be more efficient, since accelerator parameters can be varied independently. The decoupling of even correction elements is much more difficult when the two machines are close to each other.

(c) Decoupled rings allow for optimal transverse location between rings, particularly for insertion of conventional (non-superconducting) elements in the two rings. Although soluble with coupled magnet systems, the design and construction of utility areas will likely be more difficult and more expensive. Operation is also likely to be more difficult.

3. (continued)

(d) The ability to select magnets for their location in the ring so as to cancel small errors in field quality is easily achieved in the one-in-one design.

4. You noted that the complexity of the superferric magnet has increased with time. What were some of the technical factors which led to this increase in complexity?

The original superferric concept involved very long single magnets in single cryostats with a single major coil at a typical current (~ 6000 A). The field quality at low and high fields was to be maintained by shaping of the iron pole faces of the magnets. This has apparently not been possible. The present design for the "C" magnet has three dipole magnets in a single cryostat, with a complicated assembly for coupling the many current leads between magnets inside the cryostat, which is able to compensate for the shrinkage (about 30 cm over the entire length) that occurs when the magnet is cooled to liquid helium temperatures. Maintenance of reasonable field quality has necessitated the use of three major coils to excite the magnet; two of these must carry currents of order 12,000 amps. The currents in these coils depend in a complicated (i.e. non-linear) way on the desired magnetic field. Furthermore, a magnetic shunt has had to be introduced at the edges of the gap to aid mechanical assembly.

In the original concept, furthermore, it was hoped that simplicity of construction would come about by a design which relaxed the tolerances on the location of the superconductor. In fact, the "C" magnet design requires similar conductor placement tolerances as the cosθ magnet. In addition, there are stringent tolerances on the constancy of the magnetic permeability for the iron laminations in the C-design, which is not required in the cosθ version. Although soluble in principle, these problems require a data base for the effects of parameter variation. This data base does not exist. Measurements of field quality in the superferric magnets is complicated by the elliptical beam pipe, which presently limits the precision of field quality measurements.

5. What remaining R&D needs to be done on the cosine-theta magnets, and what is the estimated cost for this R&D?

Accelerator quality cosθ magnets are in hand, thus demonstrating technical feasibility of this design. What remains then is development for cost reliability optimization and cost validation. This includes fabrication of a sufficient number of full size models for system tests, significant industrial involvement in streamlining the magnet design for production, and in the design of cost effective manufacturing plans with concomitant cost estimates and continued development of improved superconductor. In my view, an investment of up to $30M in these activities would likely generate worthwhile payback in terms of magnet capital cost and long term operating expenses. I might add that, were the superferric design at the same stage, a like amount would be required for its cost reliability optimization. How much additional R&D would be required to bring the superferric design to the present stage of cosθ development is unknown.

6. The Fermilab Tevatron was used as a basis of experience for the high field magnet. The Fermilab Tevatron has operated the first two years at or below 800 GeV corresponding to a field of 3.6 Tesla, well under the design field of 4.5 Tesla. How do you consider this relevant to 6.4 Tesla magnets for the SSC? Might we expect the SSC to operate the first two years at 80% of design?

Fermilab's TEVATRON (or Energy Doubler) was the first superconducting synchrotron ever built and it is logical to assume that SSC will profit enormously from the experience obtained by what was a beyond-the-state-of-the-art project. The decision to operate at 800 GeV (actually the design energy) was governed by the desire to achieve the maximum reliability consistent with a substantial energy increase over the old 400 GeV machine.

The limitations at Fermilab came from two factors. Some 25 (out of 776) magnets were installed in the ring in spite of the fact that measurement indicated they would be marginally operable near 900 GeV. These variations in magnet quench currents arose from variations in the quality of superconducting materials delivered during the years 1979-82 when the magnets were fabricated. The marginal magnets were installed to avoid delays in the commissioning of the new machine. Another factor had to do with the amount of refrigeration which had been planned to cool the ring. Here again necessary modifications in the assembly of magnets created a burden on the refrigeration which used up all the reserves.

The 800 GeV operation was programmatically acceptable for the approved physics experiments and so was continued during 1984-85. During the 1985 long shutdown, Fermilab is replacing the weak magnets. The Laboratory Directorate states that they plan to run at 900 GeV starting in October 1986. Improvements in refrigeration will take place during 1986-87 (depending on available funding) to bring the energy to 1000 GeV.

6. (continued)

The SSC has the tremendous advantage of having had a reasonably scaled prototype (TEVATRON) whose experience can be incorporated into all aspects of the design.

A statement by the Fermilab Directorate on this question follows: "The design value of the magnetic field in the cosθ type magnets of the TEVATRON is 4.35 Tesla. Tevatron operation during the past two years has been at a field level of 3.48 Tesla (800 GeV) primarily in order to achieve optimum reliability consistent with substantial increase in energy from the old 400 GeV machine. The magnets in the Tevatron have been powered to a field of 3.92 Tesla in recent testing. We expect to increase this value to 4.13 Tesla as soon as a relatively few magnets (25 out of 774, or about 3%) are upgraded and some minor problems with other systems have been corrected. The 5% discrepancy with 'design' field comes from a decision to shorten each dipole by 5% at an early stage in the fabrication process in order to allow room for correction coils. There is no reason from TEVATRON experience to fear that an SSC constructed from magnets similar to the presently proposed 6.6 T will not achieve the design specifications. Although no one can assert that the SSC magnets will have no errors - the TEVATRON experience, a 1000 magnet prototype with what will be at least four years of operating experience, reduces the technological risks of SSC errors to a negligible factor."

Westinghouse
Electric Corporation

Research and Development Center

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COMMITTEE ON SCIENCE
AND TECHNOLOGY

December 13, 1985

The Honorable Don Fuqua
Chairman
Committee on Science & Technology
U.S. House of Representatives
Suite 2321, Rayburn House Office Building
Washington, D.C. 20516

Dear Mr. Fuqua:

Thank you for your letter of November 27, 1985 relating to my testimony on October 29th, 1985 before the Subcommittee on Energy Development and Applications regarding the selection of magnets for the SSC accelerator.

I am enclosing with this letter my answers to the seven additional questions which Members of the Subcommittee have submitted.

Yours sincerely,

John K.

John K. Hulm
Director
Corporate Research and R&D Planning

mg

Enclosure

Question 1

Is now an appropriate time for industry to become involved in the SSC magnet design, and if so what level of funding might be appropriate at this stage?

Answer

It has to be stated that to a certain extent Industry has been involved for at least two years with the SSC magnet development program. For example, industrial scientists and engineers have attended many seminars on magnets at the various National Laboratories. Several individual companies have located engineers at various National Laboratories (at the company's own expense) to work as 'guest workers' alongside the Laboratory engineers.

Brown Boveri, General Dynamics and Westinghouse have carried out engineering studies on cosine theta magnets for SSC. Design and prototype production work on the Superferric style has been carried out by General Dynamics.

I think the real thrust of this question is, should the Industrial Involvement in the SSC magnet development program be intensified? The answer to this question is a resounding YES!, for the following reasons.

The cost estimates for the production of the high field magnet system for the SSC approach 1 billion dollars. It appears highly desirable that such an expensive system should be constructed by private industry, with competitive bidding to procure the system at the lowest possible cost, subject to adequate technical performance.

There is extensive technical experience in U.S., European and Japanese Industry on the construction of superconducting magnets for applications such as Fusion, MHD, electric power generation and Magnetic Resonance Imaging. However, Industry in the U.S. has relatively little experience with HEP accelerator magnets, primarily because these specialized, small bore, race-track type magnets have been mainly developed in the U.S. National Laboratories.

It follows that if Industry is to do a good job of manufacturing the SSC magnets, the technology must be transferred from the national laboratories to Industry. We need TECHNOLOGY TRANSFER, but for a sophisticated technology of this type it will be necessary for the national laboratories ~~to~~ do more than merely pass the models, documents and machine drawings over to industry. For successful technology transfer, it is vital for engineers from industry to be involved in the magnet development program at the earliest possible stage.

One might compare this process to a relay race in which the baton must be passed from one runner to another as the race progresses. But the passing of engineering and production knowledge is much more complex than baton passing, hence the need for the longest possible involvement between the technology generators (national labs) and the technology recipients (industry).

It is my understanding that the Central Design Group and the various laboratories engaged in magnet development for the SSC are planning to arrange a stronger involvement with industry in 1986 and beyond, to accomplish the technology transfer.

My own opinion is that at this stage of development of the magnets, it would not be unreasonable to allocate 20% of the total magnet development budget to industrial participation in 1986. This percentage would have to be increased somewhat in the later stages of development, particularly for the development of tools and jigs, in 1987 and beyond. The production of a limited number of prototypes would be necessary, probably on a competitive basis, with a larger amount of funding, as a precursor for competitive bidding for the full production cycle.

Question 2

Is Industry also willing to provide additional private resources in addition to government funding at this point?

Answer

As I have stated in the answer to question 1, several industrial companies have *already* provided some limited private resources to send their engineers at company expense to the national laboratories to perticipate in seminars and to work alongside the national laboratory personnel.

The question as to what might happen in the future cannot be answered in a generic sense; it is a decision that each company has to make for itself, the chief question is, will the value of the technological experience gained in the project plus the profits (if any) received from the production contract (if won) warrant an up-front investment in cost-sharing in the initial development program?

The industrial development contracts will presumably be placed by the national laboratories or by the Central Design Group. These agencies will be in a position to seek cost-sharing from industrial companies if they desire to do so.

Question 3

Do you believe that the magnet pre-production and systems test programs should be conducted at laboratory sites, such as Brookhaven, or could these more appropriately be carried out in an industrial setting?

Answer

The National Laboratories are particularly well qualified to perform certain important tests, particularly the cryogenic tests and especially tests of magnet strings at liquid helium temperatures, where large refrigerators are required to provide adequate cooling capacity. These large helium refrigerators are already in place at Brookhaven and Fermilab.

I would expect the National Laboratories to continue to carry out cryogenic tests on pre-production, since it would not be cost-effective to duplicate this testing capability in Industry, and the magnets are expected to be easily transportable.

Of course, Industry will perform as many tests on the magnets as are possible within its own facilities. With the cosine theta magnets, useful magnetic field profile data can be obtained with low-current excitation at room temperature. Some companies already have helium refrigerators available to perform smaller scale (single magnet) testing, so these could be utilized without additional expense.

During the production phase, industry should perform sufficient testing to ensure proper performance. This approach will minimize feedback time to uncover any production problems before large quantities of magnets are either in transit or inventoried at a central acceptance test site.

In speaking of industry here, I have been referring primarily to the magnet constructors. Of course there will be a strong involvement by other industrial contractors in the magnet system, in particular the suppliers of the superconducting wire for the magnets. There will have to be a good deal of cryogenic testing relative to quality control for this superconducting material, but facilities already exist at the materials companies as well as the magnet companies to perform this work.

Question 4

You state in your testimony that the TAC magnet is two years behind the high field magnet in research and development. General Dynamics, however, has stated that 24 of the TAC magnets could be built during 1986. The high-field magnets, by contrast, are not scheduled to be built until 1988. How do you explain this?

Answer

I cannot find any direct reference to the General Dynamics quotation that they could build 24 TAC magnets in 1986, but I have checked with Dr. Raymond Beuligmann and we do not think there is inconsistency between this statement and the statement made for the high-field magnets, for the following reasons.

It would certainly be possible to construct 24 of TAC magnets in 1986. Similarly, 24 cosine theta magnets could also be built in 1986. The reason why it would be foolhardy to make either of these steps, at great expense, has to do with the state of development of each of these magnets. Please permit me to say a few words about the process of engineering development.

The engineering development process is one of iteration. The engineer designs a new device as best as he or she knows how, and builds a prototype. The prototype is tested thoroughly, generally revealing faults, failures, problems, inadequacies, difficulties of fabrication and high costs in certain parts, as well as poor performance characteristics and/or excessive sensitivity to outside parameters such as vibration, shock, temperature, etc., etc. The first prototype is redesigned to eliminate these problems, but usually this process has to be repeated several times before design acceptable for production is realized.

Usually the basic layout and the special materials utilized are changed several times in this process.

The main results of the development process are that both performance and reliability are improved. Also, the COST CONTINGENCY FACTOR (for production) tends to decline as the development process continues, simply because unknowns are eliminated and the yield of satisfactory manufactured devices is increased.

It will be obvious from what has been said already that performance and reliability are usually improved as more and more prototypes and production devices are built. It is not just a question of elapsed time, but also depends upon the intensity of the effort.

Now in the case of the superferric magnets, we can trace about 17 prototypes which includes two 28 meter length magnets to date. The majority of these were constructed in the past 3 years, mainly at the Texas Accelerator Center. In the case of the high field (cosine theta) magnets, approximately 1,300 have been constructed altogether since 1973, with 900 in service at Fermilab in the Tevatron. This service has been, in general, satisfactory; it is clear that great improvements in the SSC cosine theta magnets will be possible as a result of the Tevatron experience.

As we compared these two magnet styles at their individual states of development, we concluded the superferric to be at least two years behind the cosine theta style at this point in time (August 1985). This is primarily due to the huge number of development iterations and tests involved in the Tevatron experience. We have also taken into account the increasing complexity of excitation in the Superferric case. Possibly the development gap is even greater, but two years seems a reasonable assessment. For example, during the development of the Tevatron, a total of five years elapsed between the completion of the first full length dipole prototype and finalizing the design concept for production. Design revisions during this period included the incorporation of collars to improve conductor support and kapton for insulation. In addition, the magnet was shortened to accommodate interfacing correction coils and "smart bolts" were added for proper alignment. In our opinion, the Tevatron magnet experience is a representative example of the interaction process which generally occurs in any major engineering development program. Additional design iterations further maturing the cosine theta design have occurred over the past three years while the national labs have fabricated nearly 40 model magnets for SSC.

To summarize our opinions, (1) from August '85, approximately two more years of development will be required to bring the advanced cosine theta design to a state where production can begin in Industry. (2) At least two more years of development will be required to bring the Superferric design to a level where the cosine theta magnet is now (August 1985) plus a further period of about two years to bring it to a state ready for mass production. (3) The two extra years of development for Superferric may be reasonable if, at the end of the period, we could build a much lower cost or better performance accelerator. Present evidence indicates that this is not the case.

Question 5

Please provide a list of cosine theta high field accelerator magnets that have been constructed in American Industry and their success, magnetic field obtained, and the design field.

Answer

The literal answer to this question is, 2. Two cosine theta prototype magnets for the Colliding Beam Accelerator at

Brookhaven National Laboratory were constructed by Westinghouse in 1979, using a braided cable design due to BNL. The magnets eventually reached the design field of 5 Tesla, but exhibited severe training which made them unusable. Subsequently the braided cable was replaced by a Rutherford Cable, which worked satisfactorily.

Two other comments are relevant to this question:

(1) The German part of Brown Boveri has up to now constructed the nine cosine theta magnets in the past two years listed below:

	Project	No	Design	Obtained
Cold Iron Type	HERA	3	4.5T	5.9T
Hybrid Type	RHIC	4	3.5T	4.8T
Hybrid Type	HERA	2	4.7T	5.5T

All of these magnets performed satisfactorily.

(2) Under conditions equivalent to Industrial production, Fermi National Accelerator Lab produced 906 cosine theta dipoles for the Tevatron. All of these magnets reached their design field of 4.4 T and to date only two have experienced serious failure in service.

Question 6

Please provide a list of Superferric accelerator magnets that have been constructed in American Industry and their success.

Answer

It appears that for the Superferric style, two complete magnets were constructed to date by General Dynamics. One of them, of 1 meter length (a small prototype) performed satisfactorily on field at 2.8 T. ~~T~~he other, a 28 meter proto-type, has still to be tested.

Question 7

In your statement, you said, "We feel that the cost contingency factor for the Superferric stype should be greater than stated". What is the reason for this omission?

As indicated in the answer to question 4, under the discussion of the development process, I stated that the cost contingency factor tends to decline as the development work advances and unknowns are eliminated. Thus, one would expect that cost contingency would be lower for a more mature design (such as cosine theta) than for a less mature design (such as superferric).

In the cost estimates for the two styles, the same contingency factor was used for each. Probably this is incorrect, the value should be increased somewhat for the Superferric style. However, this is a secondary effect in the sense that even with the same contingency factors for both styles, the Superferric seems less attractive.

Rohrer Associates Inc.
Management, Engineering, Construction Consultants
E. Parke Rohrer P.E. President

December 11, 1985

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COMMITTEE ON SCIENCE
AND TECHNOLOGY

Congressman Don Fuqua
U.S. House of Representatives
Committee on Science and Technology
Suite 2321 Rayburn House Office Building
Washington, DC 20515

Dear Mr. Chairman:

In response to your letter of November 27, 1985 requesting answers to additional questions from your Subcommittee Members, you will find the enclosed information. I trust that this will meet the needs of the Subcommittee.

Thank you for the honor of appearing before your Subcommittee.

Very truly yours,

E. Parke Rohrer

E. Parke Rohrer, P.E.

enc.
EPR/j

P.O. Box 58 Strasburg P.A. 17579 [illegible]

QUESTIONS PUT TO PARKE ROHRER BY REP. FUQUA - letter of 11/27

Question 1.

While the "median site concept" for estimating the costs for tunnel construction is excellent and covers a wide range of soils that could be encountered, how could the actual costs for a specific site vary from a more difficult site and for a less difficult site?

Answer 1.

Possible cost variations for various rock/soil/construction types were included in the median site concept. They included Type I tunnels in rock, Type II tunnels in soil, and Type III "cut-and- cover" tunnels in soil. The costs estimated for these three tunnel types were $1160/ foot, $1100/ft and $770/foot, respectively. The contingency factors which were applied to these tunnel types were plus-or-minus 25%, 30% and 20% respectively. The net result of applying these contingency factors to the base estimates is a cost range from $640/foot for a less difficult "cut-and-cover" soft ground tunnel to $1450/ foot for a more difficult rock tunnel.

Question 2.

Dr. McIntyre mentioned that civil engineers at the Texas universities have invented a new tunneling technology that promises to significantly increase tunneling rates and reduce costs. Are you familiar with this technology, and, if so, do you agree with the claims made for rates of tunneling advance? When do you think this technology will be deployed to the field and put to actual practice?

Answer 2.

Yes, I am familiar with the methods proposed. It was discussed it some detail with the tunnel consultants review board which has been assisting the CDG. The method is innovative and interesting, but unfortunately has not been put to the test of actual construction conditions. The extruded tunnel lining used in the proposed method has merit, and it is expected that support for this approach will be recommended to the DOE. As noted, the technology has not been established, so there is no way to state when or whether it might be deployed. One aspect of the proposal, the Extruded Tunnel Lining System, is under development at the present time under the auspices of the National Research Council Canada. This development is being followed by the SSC Central Design Group. Assuming that the materials research aspects of the study are successful, then a demonstration in the field is being projected for approximately two years from now, provided the necessary support is forthcoming.

Question 3.
What new tunneling technologies are likely to be used in practice in the next 10 years to reduce the costs of tunneling from those figures derived from the case histories and data on the 84 tunnels used by the U.S. National Committee on Tunneling Technology?

Answer 3.
In addition to the extruded, tunnel lining system advocated by the Texas Universities, several schemes for precast concrete segmental linings which can be placed rapidly with simplified fastening systems are of interest. Rock boring machines with automated regripping, feedback control of cutter thrust, larger cutters, improved cutter materials and shapes, and water jet cutters are also being developed or considered for development at this time. From discussions with contractors, equipment manufacturers, and geotechnical consultants these developments are ones that could be introduced in time to effect potential cost savings for the SSC.

Question 4.
You have presented "normalized" tunneling cost data. In actual practice, do these costs vary significantly with geographic location for the same soil types? Given the cost estimates ranging from over $400 million to over $750 million, please provide the ranges of cost variations of labor and materials for different geographic locations?

Answer 4.
Yes, there are significant cost variations for tunnels constructed around the United States. Even for the same soil, significant cost variations will be introduced by ground water conditions, local materials costs, equipment costs and availability, topography, site accessibility and available roads, distances to disposal sites for excess soil, local labor costs and practices, size and skill levels of the local labor pool, costs and availability of housing for the construction labor force, economic state of the local construction industry at the time of the project, and variations in safety requirements and practices. The analysis undertaken by the CDG for use by the MSAP, was based on national averages for cost estimates. Established construction indices would indicate that there could be variations about the national average by as much as plus or minus 25% depending on geographic location and local labor practices. Such cost variations will no doubt be considered by DOE as they evaluated potential sites for the SSC.

Question 5.

How much cover over the concrete shell is required for radiation protection, and how much cover would be required for a steel shell? Would these differences lead to significant cost variations?

Answer 5.

At least 20 feet of soil is needed to cover the tunnel to protect individuals against radiation from a possible, but unlikely, loss of beam. Somewhat less soil would be needed if a steel shell were used. If a 1 foot steel shell were used in place of a 1 foot concrete shell, the 20 feet of soil would only reduce to 18 feet. Considering the increased cost of the steel, this is not a cost effective solution.

Question 6.

Has a concrete shell been chosen for the SSC tunnel and, if so, what was the basis of the decision?

Answer 6.

No decision has been made concerning the detailed design of the tunnel enclosure for the SSC, since that will depend upon the specific conditions at the site chosen by DOE. Under most conditions only a relatively thin steel or concrete shell would be considered. In favorable conditions the shell or tunnel lining might be eliminated entirely.

Question 7.

From your own data there are tunnels in the U.S. from $400 to $1100 per foot, not including EDIA and contingency. You used $930 per foot. Why is it not plausible that the U.S. Government could construct the tunnel closer to the $400 per foot cost?

Answer 7.

First of all, I must point out that the tunnels displayed in the histogram that accompanied the CDG presentation covered tunnel costs that went from $400/ft to $1400/ft, a considerably wider range than was recognized by your question. It must also be noted that these are estimated costs, not actual costs for completed tunnels.

Having pointed that out, you will also observe that the weighted average tunnel cost of $930/ft is in the middle of the range of data. The variation of estimated tunnel costs reflects differing technical, geological, and workplace considerations around the country. The use of an average value for tunneling costs seems to be prudent considering the unforeseen conditions on a site that is yet to be selected someplace in the United States.

As I pointed out in my testimony, I doubt that it would be possible to realize the lowest tunnel cost estimate. The estimated costs at the lower end of the distribution represent situations that would very likely not be applicable on a federally funded construction project, considering labor agreements and safety requirements.

Question 8.

The tunnel in the SSC is a large fraction of the total cost. The tunnel will be more than 50 miles of the same cross-section at a cost of approximately one half billion dollars (including EDIA and contingency). Would you please comment on possible R&D on tunnels and tell me why R&D is not being done on tunneling in light of the possible savings?

Answer 8.

There are a number of promising short-term developments, some of which were noted in the answer to question 3. A considerable amount of tunneling R&D has been undertaken by the DOD in conjunction with the MX and Deep Basing Missile Programs and by DOT in conjunction with highway and transit programs. Information from these programs is being incorporated into the R&D program that is currently being formulated by the CDG.

Mr. **Fuqua**. Our last witness is Dr. Maury Tigner, director of the SSC Central Design Group at the Lawrence Berkeley Laboratory. We'll let you be the cleanup hitter.

Dr. **Tigner**. Yes, sir. Thank you very much, and I'll try to be brief and to the point.

[The biographical sketch of Dr. Tigner follows:]

Maury Tigner

Born April 22, 1937, Middletown, NY.
Married 1960, children 2.

Advanced Education

Attended Webb Institute of Naval Architecture.
B.S., 1958, Rensselaer Polytechnic Institute, in Physics.
Ph.D., 1963, Cornell University, in Experimental Physics and Electrical Engineering.

Present Position

Director, SSC Central Design Group, Universities Research Association, June 1984–

Previous Position

Research Associate, Cornell University, 1963–68.
Senior Research Associate, Cornell University, 1968–77.
Professor of Physics and Staff Member of the Laboratory of Atomic and Solid State Physics, Cornell University, 1977–present.

Memberships in Professional Societies

Member, American Physical Society.
Member, American Vacuum Society.

STATEMENT OF DR. MAURY TIGNER, DIRECTOR, UNIVERSITIES RESEARCH ASSOCIATION, SSC CENTRAL DESIGN GROUP, LAWRENCE BERKELEY LABORATORY, BERKELEY, CA

Dr. **Tigner**. Ladies and gentlemen of the subcommittee, I'd like to thank you for this opportunity to describe the present status of this very exciting research and development program. Over 2 years have now elapsed since the SSC was given the highest priority by the U.S. high energy community. Shortly after, in the fall of 1983, the Department of Energy formally initiated the R&D phase for this potential facility. The developments in the physics world during the past 2 years have strengthened the arguments for the SSC. Furthermore, the national effort devoted to the SSC R&D during the time has provided us with firm evidence that the SSC can be built with the existing technology and within the cost estimates originally calculated a year and a half ago. I'd like to take a few minutes today to describe some of the accomplishments of this R&D effort, and to tell you about our plans for the future. I'd also like to touch briefly on the important subject of international collaboration, if I have a few minutes at the end.

The main objectives of the R&D effort are to develop and optimize the components necessary for construction of the SSC. Because the magnets are by far the single most expensive and most critical element of the SSC, the major effort during the past 2 years has been directed in this area.

Second, to perform systems tests of the magnets and the associated cryogenic and control systems, and thus to optimize the systems aspects of the proposed machine. Third, to define the requirements that have to be satisfied by potential SSC sites. And fourth, to prepare a complete conceptual design of the SSC, including a detailed cost estimate and the projected schedule for the construction, tests, and startup of the whole facility.

It was our initial belief that a 3-year period would be sufficient to accomplish all of these goals and provide firm data on the basis of which the SSC construction could be approved with full confidence in its success. Even though the level of R&D funding has fallen short of our initial expectations, we still believe that the initial target date can be met without undertaking any unacceptable risks. We have this confidence because we have been able to concentrate our limited resources on those problems that needed to be resolved before a final conceptual design can be generated.

Important milestones in fiscal year 1985, which has just passed, were to develop site criteria for the SSC; to select a basic magnet type for complete development; to verify power requirements for the SSC; and to continue development of the superconducting materials and cable. All of these milestones have been met.

The site document, as you know, was submitted on schedule, and with DOE's permission was made available to all interested parties. The requirements, as it turns out, are not very restrictive. There are indeed many potential sites all over the United States, regardless of which magnet technology is postulated.

I will not take the time to go through the major points here, but you have all seen a copy of this, I'm sure, and see that it treats the entire gamut of things that one would have to worry about, from the physical setting to the climate and cost and scheduling factors. I'll be happy to answer questions about it, if there are any.

No. 2, a vigorous effort has been conducted to perform engineering and design studies of five basic magnets. This has been a truly national effort with participation of several major U.S. national laboratories, universities, and industrial firms, and has resulted in a data base for an informed magnet choice—of which you've just heard.

Based on this work, a conductor-dominated, high-field magnet was chosen in September of 1985 as the basis for the conceptual design which is now underway. And I've attached to my testimony, which I hope you will include in the record, the file memorandum which describes how that decision was made and some other factors surrounding it.

An extensive research effort into cryostat construction has resulted in a design that will significantly reduce the heat load on the refrigerator plant, and thus result in significant operating power savings as projected in the reference designs study. And I might add, since the subject of operating power and how it hampers the ongoing experimental work of the U.S. high energy physics program, the nice thing about the SSC is that this technology allows us to cut back on the amount of power it takes to run a large laboratory. In fact, the projected operating power for the SSC will not be more, but will be less than the operating power now required for our major accelerators.

A vigorous industry-university-national laboratory cooperative effort on improvement of the superconductor cable has resulted in a cable of current-carrying capacity that has already exceeded the expectations which were put forth in the former reference designs study. If I have time later, I'll show you some pictures on that.

Two points need to be made here which summarize the results of this development effort. First, the key assumptions that have been made in the May 1984 reference designs study have been already confirmed or even surpassed. Second, our demonstrated ability to produce superconducting magnets of different types, which invariably have met the original design specifications, shows that the making of these magnets is a well understood engineering science rather than a delicate art that it was a decade ago. Thus, one can have confidence that mass production of high quality superconducting magnets can be achieved for construction of the SSC. This belief is strongly reinforced by the operational experience of the Tevatron, a synchrotron-based on some 1,000 superconducting magnets, that has now been operating and producing physics results for over 2 years.

I'd like to turn next to our plans for the future. Now that the basic magnet style has been selected, we are proceeding with the optimization and testing of full length prototypes. We expect to have the first full length dipole magnet in its cryostat and ready for testing next April. Industry is already heavily involved in key areas of superconducting accelerator magnet technology. Now that the basic SSC magnet type has been determined, it is desirable to involve industry as soon as possible in the remaining magnet R&D from detailed design through assembly. A request for supplemental fiscal year 1986 funding for this purpose has been submitted to the Department of Energy.

The magnet development effort to date has emphasized strongly the dipole, that is, the bending, magnets, since these are the most numerous and most critical components of the machine. With the critical work in this area behind us, we are now ready to commence prototyping of other accelerator components, like the focusing magnets and the orbit correction system.

The results obtained from the ongoing research and development effort will be used to prepare a conceptual design report of the SSC by the end of March 1986. This will be a nonsite specific cost-optimized design of the technical and conventional systems. It will supply the technical and cost information needed for a DOE decision on whether to proceed with the SSC.

I should say a few words at this time about the systems test, sometimes called the string test, of the magnets. The prototype magnets, whose production is now beginning, will be fully tested individually, of course, after they are produced. In addition, we are planning to perform a systems test designed to study their behavior as part of a complete system, and at the same time test other large systems like cryogenics and controls. During the fiscal year 1986 period, preparations will be made for this systems test, and the plans are to commence this test early in fiscal year 1987, as soon as several prototype magnets are available.

If the needed budget support is forthcoming for fiscal year 1987, industry-made prototype magnets will be available during 1987 and they will be tested at that time to ascertain that magnets mass produced by industry satisfy all the potential SSC requirements. In parallel with all the magnet development and construction, work will be performed on other acceleration systems like cryogenics, radio frequency cavities, injector components, and controls. The ultimate design of the accelerator complex must, of course, await decision on the siting. We hope that this decision will be made before the end of fiscal year 1987 so that construction could start in 1988.

I would like to conclude my remarks by discussing briefly the extent of international involvement in the SSC, a subject which we have already heard about today, but which is on the top of all of our minds, of course. Because of its reliance on large and, hence, expensive research facilities, particle physics has always had a strong international flavor, with physicists from one country frequently using accelerators in other parts of the world. Furthermore, there are several instances—for example, CERN—of international cooperation on construction of accelerators, although this kind of collaboration has been limited to date to countries within one region. Because of its size and large initial cost, SSC is an ideal candidate for possible interregional collaboration on the construction phase. The high energy community in this country views with favor such a possible development. But because of the inherent complexity of such arrangements, the lead here must be taken by the governmental officials. In the meanwhile, however, we have been making efforts to collaborate on SSC planning with our European and Japanese high energy colleagues.

In assessing the extent of what is possible in this area, one must take cognizance of the level of commitments of our foreign colleagues to their own domestic programs. At the present time, there are two large accelerator construction projects underway in Europe, LEP and HERA, as you've heard in some detail today. These two programs will absorb most of the European human and financial resources at least until the end of the decade. In Japan, the situation is similar with construction and commissioning of the $e^+ e^-$ collider Tristan, which will occupy their high energy community and some of ours for probably another 2 years. For now, our colleagues abroad are clearly preoccupied with their own vigorous accelerator construction programs. But as these programs mature, possibilities for collaboration may very well develop.

There has been significant interest expressed in the SSC by foreign physicists. We have received substantial help from both our Japanese and European colleagues by virtue of their participation in a number of SSC advisory panels, task forces, workshops and other planning activities. As a single example, the Magnet Selection Advisory Panel, which made the recommendation to me on the magnet style we should choose, included three foreign members and consultants.

The Canadian high energy community, at the annual meeting of its Institute for Particle Physics, has adopted a resolution strongly supporting the SSC and expressing its interest in collaboration. Cooperative efforts have been going on with the Japanese on understanding the effect of synchrotron radiation emitted by the 20 TeV protons on the quality of the vacuum in the beam tube. That collaboration has been formalized within the framework of the United

States-Japan agreement on collaborative efforts in high energy physics. Recently, and perhaps significantly, a joint United States-Japan subcommittee has been formed to explore and review past joint efforts and make recommendations about their possible extension into the future.

To conclude, we can all celebrate the progress that has been made in the research and development effort on the SSC. There has been a broad national involvement in this work, with significant foreign participation. Technically, the SSC today rests on a much firmer footing than it did at the time of the reference design. In the intervening period the physics research needed for the SSC has been examined continuously and has been strongly reaffirmed. In early 1986, a conceptual design and detailed cost estimate will be delivered to the DOE for its consideration.

And in view of the shortness of the time, I think I'll forgo the pictures, unless by public demand.

Mr. **Fuqua**. Unless somebody wants to get gavelled out of order, I think we'll forgo that. Not that we would not enjoy seeing them sometime.

[The prepared statement of Dr. Tigner follows:]

RESEARCH AND DEVELOPMENT

FOR THE

SUPERCOLLIDER

M. Tigner

Universities Research Association

Testimony before

Subcommittee on Energy Development and Applications
Committee on Science and Technology
United States House of Representatives

October 29, 1985

Chairman Fuqua and members of the Subcommittee, I would like to thank you for this opportunity to describe the present status of the Supercollider research and development program. Over two years have now elapsed since the SSC was given the highest priority by the U.S. high energy community. Shortly after, in the fall of 1983, the Department of Energy formally initiated the R&D phase for this potential facility. The developments in the physics world during these past two years have strengthened the arguments for the SSC. Furthermore, the national effort devoted to the SSC R&D during that time has provided us with firm evidence that the SSC can be built with the existing technology and within the cost estimates originally calculated a year and a half ago. I would like to describe for you today some of the accomplishments of this R&D effort and tell you about our plans for the future. I would also like to touch briefly on the important subject of international collaboration.

The main objectives of the research and development effort are:

1) to develop and optimize the components necessary for construction of the SSC. Because the magnets are by far the single most expensive and most critical element of the SSC, the major effort during the past two years has been directed in this area.

2) to perform systems tests of the magnets and the associated cryogenic and control systems, and thus to optimize the systems aspects of the proposed machine;

3) to define the requirements that have to be satisfied by potential SSC sites;

4) to prepare a complete conceptual design of the SSC, including a detailed cost estimate, and the projected schedule for the construction, tests and start-up of the whole facility.

It was our initial belief that a three year period would be sufficient to accomplish all of these goals and provide firm data on the basis of which SSC construction could be approved with full confidence in its success. Even though the level of R&D funding has fallen short of our initial expectations we still believe that the initial target date can be met without undertaking any unacceptable risks. We have this confidence because we have been able to concentrate our limited resources on those problems that needed to be resolved before a final conceptual design can be generated.

Important milestones for FY 1985 were

- Develop site criteria for the SSC
- Select a Basic Magnet Type for complete development
- Verify power requirements for the SSC
- Continue development of superconducting materials and cable

All of these milestones have been met.

1) The site requirement document was submitted on schedule and, with DOE permission, made available to all interested parties. The requirements, as it turns out, are not very restrictive. There are many potential sites all over the U.S., regardless of which magnet technology is postulated.

2) A vigorous effort has been conducted to perform engineering and design studies of five basic magnet types. This has been a truly national effort with participation of several major U.S. national laboratories, universities

and industrial firms, and has resulted in a data base for an informed magnet choice.

3) Based on this work, a conductor-dominated, high-field magnet was chosen in September 1985 as the basis for the SSC conceptual design. (See attached File memorandum of 9/13/85.)

4) An extensive research effort into cryostat construction has resulted in a design that will significantly reduce the heat load on the refrigerator plant and thus result in significant operating power savings as projected in the Reference Designs Study.

5) A vigorous industry-university-national laboratory cooperative effort on improvement of the superconductor cable has resulted in a cable of current carrying capacity that has already exceeded the original expectations.

Two points need to be made here which summarize the results of this development effort. Firstly, the key assumptions that have been made in the May 1984 Reference Designs Study have been already confirmed or even surpassed. Secondly, our demonstrated ability to produce superconducting magnets of different types, which invariably have met the original design specifications, shows that the making of these magnets is a well understood engineering science rather than a delicate art that it was a decade ago. Thus one can have confidence that mass production of high quality superconducting magnets can be achieved for construction of the SSC. This belief is strongly reinforced by the operational experience of the Fermilab Tevatron, a synchrotron based on some 1,000 superconducting magnets, that has been now operating and producing physics results for over two years.

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The magnet development effort to date has emphasized strongly the dipole (i.e., bending) magnets, since these are the most numerous and most critical components in the SSC. With the critical work in this area behind us, we are now ready to commence prototyping of other accelerator components, like the quadrupole (i.e., focusing) magnets and orbit correction system.

The results obtained from the ongoing research and development effort will be used to prepare a Conceptual Design Report of the SSC facility by the end of March 1986. This will be a non-site specific cost-optimized design of the technical and conventional systems. It will supply the technical and cost information needed for a DOE decision on whether to proceed with the SSC.

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If the needed budget support is forthcoming for FY 1987, industry-made prototype magnets will be available during 1987 and they will be tested at that time to ascertain that magnets mass produced by industry satisfy all the potential SSC requirements. In parallel with all the magnet development and construction, work will be performed on other accelerator systems like cryogenics, radio frequency cavities, injector components, and controls. The ultimate design of the accelerator complex must, of course, await decision on the siting. We hope that this decision will be made before the end of FY 1987 so that the construction could start in 1988.

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In assessing the extent of what is possible in this area one must take cognizance of the level of commitments of our foreign colleagues to their own domestic programs. At the present time, there are two large accelerator-construction projects underway in Europe, the large e^+e^- collider LEP at CERN, and the ep collider HERA being built at DESY in Hamburg, Germany. These two programs will absorb most of the European human and financial resources, at least until the end of this decade. In Japan, construction and commissioning of the e^+e^- collider TRISTAN will occupy the high energy community there for probably another two years. For now, our colleagues abroad are clearly preoccupied with their own vigorous accelerator construction programs. As these programs mature, possibilities for collaboration may well develop.

There has been significant interest expressed in the SSC by foreign physicists. We have received substantial help from both our Japanese and European colleagues by virtue of their participation in a number of SSC advisory panels, task forces, workshops and other planning activities. As a single example, the Magnet Selection Advisory Panel, which made the recommendation to me on the magnet style we should choose, included three foreign members and consultants.

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To conclude, we can all celebrate the progress that has been made in the research and development effort on the SSC. There has been a broad national involvement in this work, with significant foreign participation. Technically, the SSC today rests on a much firmer footing than it did at the time of the Reference Design. In the intervening period the physics research need for the SSC has been examined continuously and strongly reaffirmed. In early 1986 a conceptual design and detailed cost estimate will be delivered to the DOE for its consideration.

10/25/85

MT:SGW:dm

Superconducting Super Collider
Universities Research Association
c/o Lawrence Berkeley Laboratory, University of California
One Cyclotron Road, Mail Stop 90-4040
Berkeley, California 94720
(415) 486-4772 – FTS 451-4772

To: File, September 13, 1985

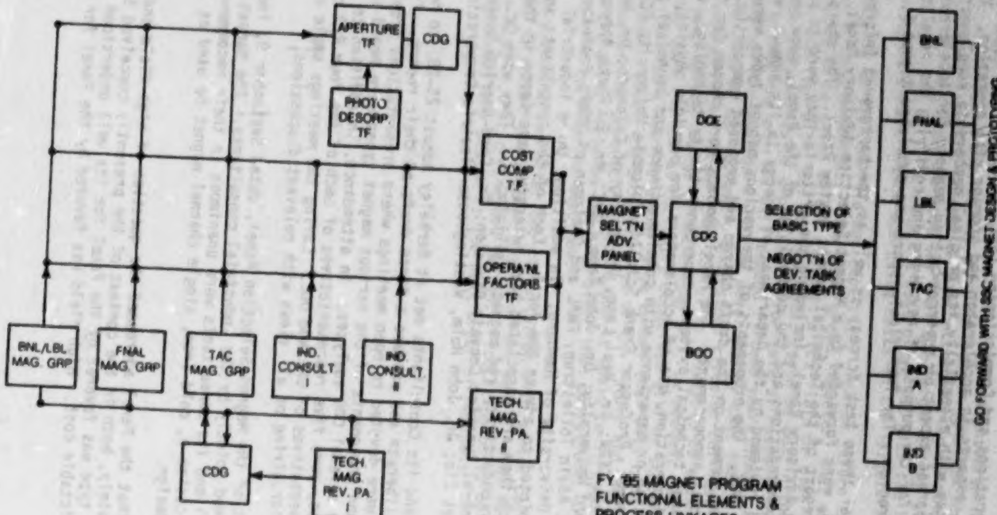
From: M. Tigner

Re: SSC Magnet Selection Process and Decision

The purpose of this memorandum is to convey the details of the selection process and the decision resulting from it.

The selection process was developed in consultation with the concerned community and made public in November 1984. It is diagramed in the attached figure. Early in FY 1985 a Technical Magnet Review Panel (TMRP) was convened to review the status of the SSC magnet R/D program and to recommend modifications to the ongoing program which would assure that the technical information needed would be available for a selection decision by the end of FY 1985. The TMRP, composed of senior representatives from the participating institutions, as well as disinterested parties with relevant technical expertise, delivered an interim report in December. Their recommendations were incorporated into subsequent agreements and contracts negotiated with the participating R/D institutions and industrial firms. Principal R/D institutions involved are Brookhaven National Laboratory, Fermi National Accelerator Laboratory, Lawrence Berkeley Laboratory and Texas Accelerator Center. Eleven industrial firms were involved in a major way in the R/D program both in the development of superconductor and in engineering studies and modeling of superconducting magnets and magnet sub-assemblies. In superconductor development the University of Wisconsin has played a central role.

In addition to the results of model tests and engineering and manufacturing process studies, selection of a suitable magnet must take the needed magnetic aperture into account. Accordingly an Aperture Task Force, directed by the Central Design Group (CDG) and participated in by the world-wide community of experts in this matter was formed. Single particle dynamics, collective effects and vacuum considerations were taken into account. All of the information provided by the above mentioned activities were supplied to two task forces formed by the CDG with broad community participation. The responsibility of the Cost Comparison Task Force was to complete detailed cost estimates of all magnet-dependent SSC systems considering, in turn, all of the candidate magnet types. The responsibility of the Operations and Commissioning Task Force was to examine the operational implications of each of the candidate magnet types. In carrying out its responsibility the CDG Cost Comparison Task Force made independent analyses but received detailed input from proponents of the various candidate magnet types as well as magnet cost estimates and manufacturing plans produced by industrial firms under contract to


APERTURE TF
CDG
PHOTO DESORP. TF
COST COMP. T.F.
OPERA'NL FACTORS TF
MAGNET SEL'T'N ADV. PANEL
DOE
CDG
BOO
SELECTION OF BASIC TYPE
NEGOT'N OF DEV. TASK AGREEMENTS
BNL
FNAL
LBL
TAC
IND A
IND B
GO FORWARD WITH SSC MAGNET DESIGN & PROTOTYPING
BNL/LBL MAG. GRP
FNAL MAG. GRP
TAC MAG. GRP
IND. CONSULT I
IND. CONSULT II
TECH. MAG. REV. PA. II
TECH. MAG. REV. PA. I
CDG

FY '85 MAGNET PROGRAM
FUNCTIONAL ELEMENTS &
PROCESS LINKAGES

XBL 8411-9009A

the CDG. The Operations and Commissioning Task Force received input from both European and U.S. experts in accelerator and storage ring operation. The TMRP, reconstituted with essentially its original membership supplemented by addition of a Japanese expert on superconducting magnets for accelerators, met during July 1985 for the purpose of reviewing and codifying the results of the SSC magnet R/D program. The TMRP final report was published August 5, 1985.

The reports of these task forces, as well as the background information supplied to them, were forwarded to a Magnet Selection Advisory Panel, along with the final report of the Technical Magnet Review Panel. The charge to the Magnet Selection Advisory Panel, including the criteria they were to use in making their recommendations and the composition of the Panel, were published in May, 1985 and reviewed by the Department of Energy in its annual review of the CDG in June 1985. The proponents of the various magnet types were given an opportunity to comment on the draft charge and proposed composition of the panel before formal announcement. The Panel members were chosen for their experience in large technical systems, superconductivity technology, accelerator design and operation, use of accelerators for particle physics, underground construction or experience with complex science and technical policy matters. They were: Professor Frank Sciulli, Columbia University (Chairman); Dr. Eberhard Keil, CERN; Dr. Neal Lane, University of Colorado; Dr. Michael McAshan, Stanford University; Dr. John Rees, SLAC; Mr. E. Parke Rohrer, Rohrer Associates; Dr. Alvin Tollestrup, FNAL and Chairman of TMRP; Professor Bjorn Wiik, DESY and University of Hamburg. In addition, three industrial consultants were appointed to advise the Panel. Each of the consultants and the firms with which they are associated have extensive experience in the technology of superconductivity and magnets utilizing it. They were Dr. Ray Beuligmann, General Dynamics Convair Division; Dr. Cord-Henrich Dustmann, Brown, Boveri et Cie; Dr. John Hulm, Westinghouse Electric Corporation.

The Panel and its Consultants met at Berkeley August 25-28, to hear presentations, deliberate and produce a first draft of their report. Two and one-half days were devoted to open meetings where presentations from the R/D participants and proponents of the various magnet types were heard as were reports on the several CDG analyses. In attendance, in addition to the Panel and Consultants, were five representatives of each of the four R/D centers, as well as representatives of URA and DOE. During the meetings ample opportunity was provided for airing of all views with relevant discussions.

The report of the Magnet Selection Panel, dated September 9, includes a statement signed jointly by the industrial consultants. The Magnet Selection Advisory Panel and its consultants were unanimous in their recommendation that a high field cosine θ, cold iron, single channel magnet be used as the basis for the SSC design.

We note that the Panel addressed the question of high field and cosine θ design separately, both in the context of the presently conceived SSC. The cosine theta type was favored by the Panel for its well understood behavior and its predictable cost. High field was favored by the Panel for operational and cost reasons. They observed that the larger transverse impedance concomitant to the larger ring implies need for larger momentum aperture and substantially more powerful rf system for the larger ring by comparison with the smaller ring. The Panel pointed out that the larger energy stored in the beam of the larger ring will increase the cost of an SSC with the larger ring and that one should expect higher operating costs in the larger ring.

The charge to the MSAP did not explicitly include future options in the criteria for recommendation. Some have urged, however, that possibilities for future expansion be given weight and that a low field be used so that a next generation collider with, say 10 T magnets, could be put in the same tunnel. I find this argument to be unpersuasive for several reasons. We do not know what beam energy the physics will demand fifteen years hence, nor do we know what technology for colliders will be developed by that time. We do know that simple extension of our currently understood circular collider technology to energies substantially larger than 20 TeV is likely to be economically infeasible and some marked change in technology will be needed. Our extensive cost studies show that the SSC as currently conceived will be somewhat more expensive if built with a low field and large tunnel than with high field and smaller tunnel. Given the uncertainties of the future and the need to minimize the cost of the presently proposed SSC it would be irresponsible to choose the operating field on anything other than operational and cost effectiveness for the collider we need now.

With this in mind and after due consultation with senior colleagues, I have decided to accept the recommendation of the panel. What has been selected is a style, not a finished design. Production of an optimized and industrially producible design is the next order of business.

MT:dm
Attachment

DISCUSSION

Mr. **Fuqua**. You mentioned toward the end of your statement about international cooperation and what has been going on, but nothing specific. Is there any more specifics other than just preliminary talk? Because it's getting down to the time to get serious about international cooperation.

Dr. **Tigner**. Well, as you know, I'm, of course, not qualified to speak about this at the highest policy levels. I can only give you the worm's eye view from the grassroots.

As you know, a number of scientific level committees and panels have been formed, both in Japan and in Europe, to think hard about the future. And particularly the Japanese are taking very seriously the possibility of collaborating on the SSC. However, as you also know, they have frequently said don't push us, we're making up our mind deliberately, we like the idea and we'll let you know what we think.

However, I have had a number of unofficial contacts, you might say, from people who are important in policy making in the high energy physics in Japan, as well as people who are high in the Japanese industrial circles, who are clearly and extremely interested in this possibility, and of course would like to proceed in some kind of formal way. And of course we are struggling to try to find such a way.

Mr. **Fuqua**. I had mentioned earlier, and I don't remember whether you were here or not, about a letter from Dr. Lederman?

Dr. **Tigner**. Yes, I remember you mentioning the letter from Dr. Lederman.

Mr. **Fuqua**. Have you seen a copy of——

Dr. **Tigner**. I certainly have.

Mr. **Fuqua**. Would you comment on the advantages and the disadvantages then that he suggests in there of a proton and antiproton collider relative to the proton-proton collider that we have, or that's being discussed?

Dr. **Tigner**. Yes. You can be sure that we are examining with great interest the suggestion of Dr. Lederman. You must understand that while it is true that it is possible to save some costs this way, and we understand that and are therefore extremely interested in pursuing it avidly, there are also basic physics questions that have to be answered and questions of technology.

For example, what would the—it isn't simply a matter of cutting the ring in half and just using one of them, it's a more complex thing than that. So, one has to examine the accelerator physics implications, if you will, of going to a $p\bar{p}$ machine.

Also, as you heard so well put from Professor Rubbia, as one goes up in energy and one is exploring phenomena on a smaller and smaller time scale, space scale, then one has to have a higher event rate in order to study the phenomena. One will expect that the basic cross section or probability for a reaction on the smaller time scale is necessarily smaller. So, the rate or luminosity, as we call it, of the accelerator must be higher in order to explore the phenomena. As we go higher in energy, we need also to go higher in luminosity.

It is true that using antiprotons in the existing synchrotron rings has been a great—was a great idea and a great step forward. And at the energy scale at which we are now working, that idea, that artifice, if you will, was very cost effective and served the science very well.

On the other hand, one of the problems with using antiprotons is their extreme rarity. You have to make antimatter in quantity and put it into this machine. As we go to the much higher energies, there is a real question as to whether the technology for making enough antimatter to fill such a big machine will suffice to produce the reaction rates we need. And of course it is on those questions that we're focusing our intense study, and you can be sure that we will get to the bottom of this before we're done.

So, it's a very interesting suggestion that's being looked at. And it's not obvious that it just solves the problem at a single stroke. I wish it were.

Mr. **Fuqua**. You noted that the national effort that's being devoted to the SSC R&D has provided us with evidence that it can be built with an existing technology and within the cost estimates originally calculated a year and a half ago.

Do you have any evidence that we can build it for less money?

Dr. **Tigner**. Well, of course our business in bringing the conceptual design report to the DOE will be to try to say exactly what we believe the case to be and back that up in great detail. It is my—I am not going to try to second guess the cost figures that we will come up with by next March.

However, I think you can look forward to some pleasant surprises because, as we've said, the remarkable improvement in the materials we're working with. The fact that we now, I think, understand the design a lot better than we did before and are able to see how to put it together in a much more effective way I think means that we certainly are on top of the costs. We have a much better idea now about the contingencies and the materials we have to work with are better.

So, I think even if you just take the straight design that we've been talking about, we can look forward to some decreasing in the cost. And of course we're looking very hard at various strategems for reducing that even further; such as the one that you mentioned from Dr. Lederman, and there are others.

Mr. **Fuqua**. Thank you. Mr. Barton.

Mr. **Barton**. Thank you, Mr. Chairman. Dr. Tigner, I want to compliment you again on providing me with materials so I can be somewhat informed in that. I do appreciate you providing those to me.

I have three or four very brief questions. One of our international experts that was here earlier, Dr. Rubbia, when I asked him the question which way would he go, would he go with existing technology in the tunnel they have in Europe, would he go with the high field design or the low field design, he basically said he wanted the one with the biggest tunnel, if I understood him correctly.

Assuming that there is another step beyond a 20 TeV accelerator collider, would you concur that if we're going to go to 40 TeV or 60

TeV that it might be better right now to go with the design that—or to build a larger tunnel or not?

Dr. TIGNER. Well, that question you asked is a good one, and it's a complex question because of the many assumptions hidden behind the general statements that are made. Professor Rubbia said he'd like to have a large tunnel. We'd all like to have a large tunnel, there's no doubt about that.

However, We have to ask ourselves exactly what would we do—what is the picture we have in mind. And the picture apparently is that we would build a certain machine and a certain sized tunnel now. We all know that research never stops, and sometime in the future you can be sure that unless there's some miracle and we get the final answers to what glues the universe together, that someone will be saying while we really are now prepared for studying the final level, so let's go to higher energy. So, let's take that picture and ask a question about that.

Wouldn't it be well, then, to right now build the biggest tunnel you could possibly think of so that no matter how big our ideas get in the future, we can just add them to that tunnel?

Well, let me—that has many ramifications to it, and the bottom answer is I don't believe that that's a correct view. I believe it would not be the right thing to do, to pick anything about the SSC, based on anything other than what we need now to do the physics that we have before us. Let me just give you two simple examples of that.

Suppose now that we were to have an SSC with a certain sized tunnel and use the kind of technology that has been proposed. I don't care whether it's the low field superferric magnet or the higher field magnet. And say OK, we are now going to—we have now somehow found a way of doubling the magnetic field, either from going to the superferric magnet to the design D magnet we're talking about, or going from the higher field magnet to yet another field magnet that surely will be coming along in the future. I mean, 15 years down the pike we could very well have magnets that may be 100 Tesla with the new materials that are being talked about. So, we can't see the future very well.

But never mind. Let's just talk about going up a factor of 2, and taking a tunnel and putting in twice as high field magnets in order to expand the energy of the machine. A factor of 2 is not very high on the scale of accelerator advances in the past, but nevertheless let's talk about that.

One of the things that's unique to the SSC is it's the first time that a circular proton machine has ever been built which will emit synchrotron radiation. As you know, synchrotron radiation is the phenomenon that has essentially limited the development of circular electron machines to the size that the LEP machine is at now. There will essentially be no more circular electron machines because of the enormous amount of radiation emitted by those beams, while with proton machines we've now gotten to the point where they're beginning to radiate, and one has to understand that the physical law that dictates that radiation is proportional to the fourth power of the energy of the machine. So to go just a factor of 2 in energy—of beam energy would cost you a factor of 16 in the power that's being emitted by the beam.

We're talking now with this technology, the technology that has allowed us to get to the high beam energies we can now talk about, is one of superconductivity, which requires the innermost parts of the magnet to be held at 4 kelvin.

The point about that is that it costs a great deal of money to cool down a system to 4 kelvin, and the refrigeration efficiency becomes very poor. So that for every watt that you remove at 4 kelvin, one must put in at least 500 watts from the power lines at room temperature, and sometimes as much as 1,000 watts. So there's a terrible multiplier there.

So, as soon as the synchrotron radiation begins to become significant, the technologies that we're now talking about will no longer be useful. We will have to think of something different. We'll have to advance some kind of a magnet system in which one could maintain the inner bore at some higher temperature for a higher thermodynamic efficiency.

So that, in fact, the cost of the system as we understand these things now is going to go up substantially. The cost for—the incremental cost per GeV will begin to rise with a characteristic more of electron machines, which go like the square of the beam, the overall beam energy, rather than as linearly with present proton machines.

So, I think we can already see that that kind of a step will not be economical with any technology that we now have in hand. That's the first remark to be made.

The second is that——

Mr. **Barton**. Believe it or not, I understand what you just said, Dr. Tigner.

Dr. **Tigner**. I'm sorry I wasn't very lucid, but it's a complex subject, of course. Secondly, there are accelerator technologies now being developed which—let me back up and say something else. The cost per GeV for accelerator facilities now is large. It has fallen enormously over the course of history, but nevertheless it's large. We're talking about spending for this science, on an instrument, an amount of money unprecedented before.

Mr. **Barton**. I agree.

Dr. **Tigner**. If we're going to take another step, we absolutely have to find a way of sharply slashing that cost per energy unit, otherwise the idea of going to a higher energy is just economically absurd.

We cannot forecast what the shape of that new technology may be. There are several technologies in the laboratory and on the drawing boards, some of which may prove out to be useful and some of them may not. The cost-effectiveness of any of them has yet to be examined in any great detail.

However, we have high hopes that they will make a dramatic breakthrough in the cost per GeV. And most of those schemes will not use circular tunnels. So, I think all I can say is that 15 years from now, when we might be thinking of upgrading the SSC, the likelihood that the capital value of a certain tunnel will have an enormous value is very, very small in my opinion. And I do not believe that we should encumber the decision on the SSC today with a larger or smaller tunnel, unless that is the way to the cheapest SSC.

Mr. **Barton**. If I may interpret that, then you—the possibility exists that high energy physics may be satisfied with a 57-mile circumference tunnel, and never request in the future a 100-mile circumference or a 150-mile circumference tunnel. Is that—I said, may; I didn't say never.

Dr. **Tigner**. At the moment—and I'm very hesitant about forecasting the future since I've heard many forecasts of the future of my young life which did not come true—I've heard the statement we've built the last synchrotron so many times now I can't even count them.

The shape of things to come seems to be the linear accelerating techniques, which are likely to prove the most cost effective for the very highest energy accelerators.

Mr. **Barton**. With the design that's been chosen, it's basically two magnets separate. Is there a possibility that you could combine those two into one and save some money and have the same cryogenics for the same—for both magnets?

Dr. **Tigner**. Yes; that's a possibility. We looked at that once. It has some disadvantages, too, in terms of operations. I mean, whenever one ring has stopped they're both stopped, or when one loses the beam in one, it's quite likely that you lose the beam in the other ring. So, we have to balance our reliability assessment. After all, the machine—we have certain objectives. To do the physics, the machine has to be on reliably for a large fraction of the time, and we have to give some economic credit to that, albeit it is difficult to do.

So, we are trying to balance the possible cost savings of going to a single envelope type of construction against the operating difficulties that will accrue when the two beams are so closely linked together. And we are studying that. I don't know what the outcome of that will be. But again, it's close.

Mr. **Barton**. Let me ask another question. The magnet design selection committee chose—of the two top designs—chose the design that according to their calculations was $83 million less in fiscal 1984 dollars.

If they were to be shown that the low field-design—or let me rephrase it. If we reverse that, and the low-field design turned out to be $100 million or $83 million less expensive than the high-field design, would you consider changing the magnet design?

Dr. **Tigner**. Well, the answer is, of course, there's much more to it than just these cost figures. It has to do with a complex of things. We want to have a reliable SSC which—in which the cost is as cost effective as possible. And so, if I had the—exactly if the two——

Mr. **Barton**. Well, let me ask a question——

Dr. **Tigner** [continuing]. Technologies were in exactly the same state, and you really have this choice that the only difference between them was $83 million, then obviously you would pick the one with the lower cost.

Mr. **Barton**. Well, I mean, somewhere in that mass of information that you gave me, they said the variance between it as far as physics and preferability it was very close, a plus or minus 5 percent or something like that. So, we've got two designs that are doable.

How much less expensive would the low-field design have to be before you feel the design decision should have gone the other way? I mean, $80 million, $100 million, $150 million, $200 million? At some point in time, the positives of the high-field design that offset cost advantages have to—there is a cost to those. And I, personally, feel that it can be shown that the low-field design is the more cost effective design.

Mr. **Packard**. Will the gentleman yield?

Mr. **Barton**. I'll be happy to yield.

Mr. **Packard**. One of the most important statements, I believe, in Dr. Tigner's testimony was that we have made the decision and are now on schedule to move forward. I think that it would be counterproductive, and if one proposal were permitted to resubmit, to so speak, in an effort to persuade a change, then obviously the other proposal would want the same opportunity. And the 3 years that have been utilized in making a decision by a very qualified panel would be left to nothing more than just the art of playing—or bouncing the football back and forth with an effort to try to persuade.

Again, I think one of the most exciting things about these kinds of large projects, and one of the first questions many of us ask, because it does involve money, every year it means significant megadollars is, are we on schedule? And I think in this case it would be totally counterproductive to even consider going back and asking them to devote another significant amount of time to rethink, to reevaluate. You're talking about two separate, different proposals. And in every case where you ask for an RFP, those RFP's are going to be based upon different criteria, different fundamental designs.

And I think that where you have a low-energy and a high-energy proposal, I think that you can—if you just simply convert that to dollars, you are trying to convert apples and oranges to a dollar sign, which I don't think is possible in this case.

Mr. **Barton**. Well, I appreciate my colleague from California's comment.

Mr. **Packard**. I know Texans don't like to lose anything.

Mr. **Barton**. I would point out that this decision was—the information was gathered over approximately a 6-month period, to the best of my knowledge. The design team met for 2 to 3 days, and there is literally a stack of material 1 foot high.

By their own admission, several of the people on the design team had not had time to read all of the information. And I'll read a statement that's in Dr. Tigner's comments. And I quote:

> Given the uncertainties of the future and the need to minimize the cost of the presently proposed SSC, it would be irresponsible to choose the operating field on anything other than operational and cost effectiveness for the collider that we need ow.

All I'm suggesting is that we should take a close look at these ost estimates and make sure that we carefully evaluate it, because y anybody's admission, if we build the SSC, we're talking about an xpenditure of at least $2 billion and quite possibly $6 to $8 billion epending on how long it takes to build.

If that takes another 2 weeks or another month to review, I ink that's time well spent. That's all I'm stating. And I wanted to ask Dr. Tigner, if in this review we see that the low-field design is $100 million less expensive, is that enough to offset the decision that's already been made? If it's not, so be it, but that's my question.

Dr. TIGNER. Well, sir, I believe I have tried very hard to not only study myself and to ask the most expert and experienced advice in the world—not just in the United States, but in the entire world—about these matters, and I believe I have determined which is the lowest cost estimate to go with, and I'll stand behind that.

However, I would be happy to argue with you in detail about every single, solitary last number. Of course, you're absolutely right that the taxpayers and all of us who support these things have to be sure that their interests are being well served. And I appreciate that. I understand that that's why I'm here, in order to see that that happens. And I will be happy to go with you through the thing in great detail to your satisfaction.

Mr. BARTON. I appreciate that.

Mr. FUQUA. Dr. Tigner, we want to thank you for being here with us. And I know you have a tough job, and we have that every day too. And I know your decision, like all others, in a professional capacity is that you want to make sure you make the right decision. And I think you people have put forth—with an excellent group of people. It's tough, but it's been my experience that the people have been very professional, and we have to trust somebody somewhere. And I think you have had a great group of people serve on the panel, and I want to commend you for a very tough, but I think a very thorough job in making what are I'm sure very tough decisions.

But I admire you, too, for being willing to stick by your guns and what you feel is right. All of the people have a very outstanding background in their field, and we are very supportive. We, as has been pointed out by Mr. Barton and others and myself, we're very concerned about the cost. We have some very difficult times facing us in the future. And any way that we can make something accomplish good science at a less cost, we're ready to bargain for that. But I think you folks have done a very outstanding job, and we want to thank you very much. And we apologize for keeping you here so late this evening.

Thank you very much.

Dr. TIGNER. Thank you, sir.

Mr. FUQUA. The hearing is adjourned.

[Whereupon, the hearing was adjourned at 6:15 p.m.]

[Questions and answers for the record follow:]

Superconducting Super Collider
Universities Research Association
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Berkeley, California 94720
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December 16, 1985

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DEC 17 1985

COMMITTEE ON SCIENCE
AND TECHNOLOGY

Mr. Don Fuqua, Chairman
Committee on Science and Technology
U.S. House of Representatives
Suite 2321 Rayburn House Office Building
Washington, DC 20515

Dear Mr. Fuqua:

Thank you for your letter of November 27, and for the opportunity to supply further information about SSC activities.

Following are the questions and responses:

1. You said that "[n]ow that the basic SSC magnet type has been determined it is desirable to involve industry as soon as possible in the remaining magnet R&D, from detailed design to assembly. A request for supplemental FY 1986 funding for this purpose has been submitted to DOE." What level of FY 1986 funding for this purpose has been requested of DOE, and what level of involvement would this entail?

A supplemental request for $5M has been made for industrial involvement in Magnet R/D. At this level it will be possible to engage up to 10 firms in a technology transfer phase in which technical representatives of the firms participate in magnet work at the laboratories now doing development work and engage up to five firms in full scale model magnet building and in preliminary design for cost effective manufacturing processes. This level of involvement will provide for effective technology transfer by observing and doing and provide a basis for evaluation of capabilities of a variety of firms.

2. How much additional time and funding would be required to consider an alternative design of the SSC?

The time and funding required would of course depend upon the alternative selected and how different it is from the design now being developed. If the alternative were a minor scope change then a few months might suffice to complete the needed design work. If a different magnet were to be incorporated into the alternative design, e.g., the superferric design, then at least two more years would be required for the needed R/D at an additional cost of at least $35M.

3. If the SSC was changed from a proton-proton collider to a proton-antiproton collider, what, if any, impact would this have on the SSC magnet selection?

Magnet selection for a proton-antiproton alternative would be based on criteria very similar to those used for the magnet selection just past. It is clear that the same magnet style would be selected for proton-antiproton service as for proton-proton service.

4. Given the SSC Reference Design and the magnet selection, what variations might decrease the cost of the project?

Cost decreases of an SSC with Reference Design parameters would be effected by a) judicious choice of site for low cost construction characteristics; b) continued development of superconductor material; c) well conceived manufacturing and quality control procedures for the magnets.

5. What is your assignment of tasks and level of funding in FY 1986 for the laboratories (BNL, FNAL, LBL, and TAC) which have been involved in the SSC activities to date? Please provide copies of specific agreements.

The FY86 tasks and associated level of funding for BNL, FNAL, LBL, TAC, and the Central Design Group are summarized in Table 5-1.

Within the structure of Table 5-1, the Laboratory tasks have been developed to provide the optimum resources within the High Energy Physics program for the highest priority goals of the SSC R&D effort. The CDG serves to establish the programmatic goals and to coordinate the agreed-upon efforts within the total SSC program.

The development and optimization of superconducting magnet systems is a primary SSC activity for which many of the defined tasks in Table 5-1 are closely coupled. Theoretical efforts at the CDG, LBL, FNAL and TAC all contributed to the SSC performance goals and specifications which formulate the criteria and parameters for magnet systems as well as other technical components. For dipole magnet fabrication, the BNL effort will provide full scale models of the "cold mass" structure. These units are shipped to FNAL for assembly into cryostats that are designed and fabricated by FNAL. Final tests of complete dipole systems will take place at FNAL. At the same time LBL provides short models that can quickly test design changes and superconductor performance. LBL will also develop models of the high gradient quadrupoles. TAC will investigate the quench protection systems that will be incorporated for the dipoles and will also develop some of the correction magnet systems that will be utilized in the spool pieces of the main ring system. Thus it is seen that all four institutions play a major coordinated role in the total SSC R&D effort that is outlined in Table 5-1 and defined in the work task descriptions. The work task descriptions that have been developed by the CDG and the respective institutions are provided in Attachment A.

Table 5-1

SSC PROGRAM PLAN - FY86

		K$
BNL		
- Superconducting Magnet Fabrication	3020	3020
FNAL		
- General Research and Development	140	3000
- Cryostat Design and Development	960	
- Magnet Fabrication & Assembly	1300	
- Magnet Measurements	600	
LBL		
- General Research & Development	120	1400
- Superconductor Research & Devlpmnt.	560	
- High Gradiant Quadrupole Devlpmnt.	270	
- Model Magnet Development Program	450	
TAC		
- Diode Quench Protection Development	550	2600
- Correction Magnet Elements	1025	
- Accelerator Physics	275	
- Superferric Magnet Program	750	
CDG		
- Administration	1160	9980
- General Support	1500	
- Project Planning	660	
- Theory	1510	
- Injection Systems	200	
- Accelerator Systems	1320	
- Superconducting Magnet Program	1070	
- Conventional Systems	2560	
		20,000

6. Is the Texas Accelerator Center requesting further funding from either the Department of Energy or the Central Design Group for any continued work on the superferric magnet, and if so, what level of funding? How is the cosine theta magnet design helped by any continuing effort on the rejected superferric design activity? What amount of money is necessary to close out the superferric design project?

As shown in the CDG/TAC Agreement, it has been determined by the Central Design Group that 750K$ is needed to close out the "superferric" magnet work in an orderly fashion. The cosine theta magnet work is not aided by further work on the "superferric" design.

7. Dr. Hulm's statement claimed that "the cost contingency factor for the superferric style [magnet] should be greater than stated." Please comment.

An important part of the magnet type selection process was cost estimates of a complete SSC built with each of the proffered magnet styles. A significant part of the cost estimate was the contingency assigned to each magnet style arising from various uncertainties in the cost assessments. These uncertainties arise from uncontrollable material price fluctuations, etc., and from uncertainties in the design due to lack of information. Both the Magnet Selection Advisory Panel and its industrial consultants pointed out to the Central Design Group that the "superferric" design was far less mature than the cosine theta design and that the estimate of cost for the "superferric" design had risen significantly in the past two years, showing that a higher contingency factor should be applied to the "superferric" style relative to the cosine theta style. The CDG had applied the same contingency factors to the two magnet styles and accepts the criticism of the Panel as valid.

Sincerely,

Maury Tigner

MT:dm

ATTACHMENT A

SSC Program FY86

Laboratory Task Specifications

A. BNL

1. Superconducting Magnet Fabrication

   a) General: Preparation of detailed technical reports describing the BNL work in all categories and preparation of drawings and specifications needed for magnet system integration.

   b) Fabrication of 16.6m magnets: BNL has the responsibility for providing the single phase assemblies for the dipole magnets and for furnishing major help with the engineering associated with integration of the dipoles with the rest of the magnet system. This category encompasses both engineering, fabrication, and testing of components and subsystems of the dipoles. Six complete cold mass assemblies are to be fabricated.

   c) Tooling additions and modifications. BNL has the responsibility for completing the tooling required for producing the full length 16.6m long magnets.

   d) Alignment, lifting, and transporting fixtures: BNL will develop and fabricate appropriate tooling and fixturing for the critical magnetic alignment and handling processes. BNL will also be responsible for preparing the cold mass assemblies for shipment and for transporting the finished assemblies to FNAL for final assembly into the cryostat.

B. FNAL

1. General Research and Development

Preparation of detailed technical reports describing the FNAL work in all categories and preparation of drawings and specifications needed for magnet system integration.

2. Cryostat Design and Development

FNAL has the responsibility for providing the cryostat enclosures for the dipole magnets and for furnishing major help with the engineering associated with integration of the dipoles with the rest of the magnet system. This category encompasses both engineering and testing of components and subsystems of the dipoles.

a) Cold Mass - Mechanical and Thermal Characterization: This work includes engineering computation and measurements of the longitudinal and torsional stiffness of the magnet cold mass itself and measurements of transfer functions of the cold mass and suspension system in response to accelerations over the frequency spectrum of interest. In addition calculations of thermal stresses in the magnet assembly during cooldown will be made.

b) Suspension System Development

i. Carry out structural analyses of present and potential dipole supports.

ii. Carry out engineering for mechanical and thermal tests of folded post supports.

c) Cryostat Design

i. Perform balance of engineering studies for DI model.

ii. Carry out performance evaluation studies of DI designs, such as failure mode analysis, structural analysis of complete assembly, heat leak calculations, and evaluation of cryostat materials.

d) Interconnection Work

i. Coordinate cold mass-cryostat interface design and magnet to magnet interface.

ii. Carry out needed interconnection design work.

iii. Make 3D models for explorations of design completeness and constructability.

e) Shipping and Handling Studies

i. Survey historical information available on measured acceleration and response of objects similar to the dipoles.

ii. Instrument shipping vehicles for cold mass to obtain measured accelerations and responses.

f) Laboratory Studies

i. Measure support heat leaks.

ii. Measure support moduli and strengths.

iii. Complete support creep measurements at shrink fit joints.

iv. Model alignment procedures to verify alignment method designs.

v. Conduct sliding tests of shield supports to evaluate potential galling.

vi. Conduct heat leak measurements of model assembly.

g) Provide spool design criteria document for spool piece cryostat and magnetic elements.

h) Assist CDG in spool conceptual detail designs and cost estimates including "modularity" studies.

3. Long Magnet Fabrication and Assembly

   a) Develop manufacturing plans and procedures including CPM, Schedule, and refined costs for long magnet fabrications.

   b) Propose drawing distribution and update scheme and implement approved scheme.

   c) Provide necessary tooling design, fabrication, and assembly space to produce final long magnet assemblies.

   d) Complete component design and procurement (Qty. = 6 units nominally).

   e) Assemble one model cryostat for testing without magnetic elements.

   f) Assemble four long complete magnets with single phase assemblies to be provided by BNL.

4. Magnet Measurements:

   a) Carry out necessary MTF modifications and upgrades required to individually test and measure dipole magnets.

   b) Propose to CDG a dipole test protocol including mechanical, electrical, and magnetic requirements. Approved protocol will become part of this agreement.

   c) Provide to CDG a test data format. Subsequent measurement data will be provided to the CDG in the approved format.

   d) Test four single magnets per approved protocol.

C. LBL

1. General Research and Development

Preparation of detailed technical reports describing the LBL work in all categories and provision of administrative support to LBL program activities.

2. Superconductor Research and Development

LBL has the responsibility for procuring the superconducting cable for the 1-m model programs and the six 16.6 m model magnets to be constructed at BNL. This task includes steps from preparing the specifications and procuring the wire through insuring final cable supply adequate for the long magnet fabrication.

3. High Gradient Quadrupole Development

LBL will develop and optimize a magnetic design including superconducting cable requirements for the high-gradient IR quadrupoles. The study will predict performance capabilities, analyze expected errors, and produce a preliminary layout to serve as the basis for a conceptual design and cost estimate. Construction and tests of a 1-m model to verify performance will be carried out.

4. Model Magnet Development Program

LBL will design, build, and test a series of 1-m model magnets. Specifically four models will be examined to qualify a high-uniformity cross-section for eventual incorporation into the 16.6 m magnets. Two model magnets will be warm tested only; an additional two models will be both warm and cold tested. The model magnets will also serve to confirm various analysis and design aspects of field reproducibility as affected by fabrication tolerances, as well as to support development of a code for precision analysis of the "as-built" magnet field uniformity. Various collar investigations will also be undertaken and measured with bench tests. Additionally, understanding of the mechanical behavior of the conductors will continue to be improved through various strain-gage measurements and finite element analysis studies.

D. TAC

1. Superconducting Magnet Diode Quench Protection Program
   - a) Assess the critical parameters. Define the system requirements for SSC magnets.
   - b) Review the existing data base. Set up meetings as required for data review and to generate new ideas.
   - c) Devise exploratory tests to compare actual performance vs. requirements.
   - d) Prepare a Summary report of (a), (b), and (c) above.
   - e) Carry out an experimental program to verify previous data and to prepare for a more comprehensive effort that will provide the data required for an optimized system for the SSC.
   - f) Review the results of (e). Devise methods for extensive tests to accumulate statistics.
   - g) Develop a comprehensive program for FY87.

2. Correction Magnet Elements for the SSC Main Ring
   a) Provide data and description appropriate for the Conceptual Design Report. This should involve a complete package with dipoles, quads, sextupoles, N-poles. This effort will be accomplished for CDR time table.
   b) Provide specifications for correction elements (December 1, 1985).
   c) Provide detailed cost estimates for correction elements in the format specified by the Work Breakdown Structure.
   d) Provide a detailed plan for the hardware required for the R&D program.
   e) Provide a detailed design for dipoles and quadrupole correction elements.
   f) Construct and test a model of the dipole corrector.
   g) Prepare and submit a detailed proposal for the FY87 program.
3. Accelerator Physics and Design Studies

   TAC will provide two (FTE) for accelerator physics efforts to expedite Beam Dynamics studies as well as other calculations that are required to optimize the design and performance of the SSC. This effort will be coordinated by the CDG Accelerator Physics Group directed by Alex Chao.
4. Final Tests and Documentation of the Superferric Magnet Program
   a) Measure four existing one-meter models of the superferric design.
   b) Measure one existing seven-meter superferric model.

c) Measure two 28-meter superferric magnet models that are being fabricated by General Dynamics:

Unit #1

Unit #2

d) Prepare a final report on the superferric magnet program (4/86).

1481c

APPENDIX 1

OCT 16 1985

Fermilab

Fermi National Accelerator Laboratory
P.O. Box 500 · Batavia, Illinois · 60510
312-840-3211 FTS 370-3211

Directors Office

October 1, 1985

Dr. Edward Knapp
President
Universities Research Association
1111 19th Street, N.W. - Suite 400
Washington, D. C. 20036

Dear Ed,

I am quite sure that your Board of Overseers is frantic by now since I have not offered advice in quite some time. Clearly this is a sad state and I hasten to remedy the situation. It seems clear to many of us that the cost of SSC is too high -- that the perception of $4, 6, 12 billion is widespread and the implanting of fear and loathing is beginning to take root in many constituencies which would normally be friendly.

It is my opinion that between now and next March, CDG, under the direction of BoO (and you), we should seriously consider the alternative design of one ring capable of supporting $p\bar{p}$ collisions at 40 TeV.

We estimate that this will reduce the cost of the machine by $600M. Another $200M should come from a more modest allocation of detector funding. When we also reduce contingency and EDIA, the estimated $4 billion everyone talks about and, widely perceived, no one out there believes, would be under $3.0B, closer to $2.8B. I make this suggestion now because I believe it (or an alternative) must be debated (quietly) for some time and if March is design completion deadline, we don't have much time.

One may have to put back $100M or so for a $\bar{p}$ source but this brings me to the more speculative but just-as-real part. The DOE already owns one injector and a $\bar{p}$ source. Thus the DOE could reasonably ask all proposing states to make offers that are roughly equivalent to this advantage. If the DOE can be convinced to think in these terms, we are really talking about a total project cost of $2.5B before international collaboration which would reduce costs even further.

Perhaps my details are fuzzy but the point is very clear. In my opinion, if we don't drastically reduce costs, SSC will die or, worse, drag out to become an unfruitful drain on the rest of the program. I realize we must do this in a way that preserves as much of the community support as possible. Whereas I believe the change in scope is minor, others seem to feel very strongly about the luminosity. The issue is whether a factor of ten in luminosity is worth $1B and the risk of a no go?

I do not think we should propose a phase II. We should note that in the late 90's, HEP will contemplate some new venture: e.g., linear collider, laser accelerator or SSC luminosity upgrade, i.e., the second ring should compete with anything else one will consider. In all of this, I have some confidence (83%) that $\bar{p}p$ can ultimately achieve $\gtrsim 10^{33}$-type luminosity, the conclusion of the '84 Chicago workshop. The alternative of reducing energy (probably to 12×12 TeV^2) is too high a physics price to pay, in my opinion. I think it is very important to couple the change in luminosity with reasonable assurance that the scientific goals can be met. We need sessions with theorists to explain to them why the goals need to be met. I lean on the EHLQ conclusions: "We are confident that a 40 TeV collider which permits experimentation at integrated luminosities of 10^{39}cm^{-2} will make possible a detailed exploration of the 1 TeV scale."

I really don't know what efforts BoO has been undertaking but the need to guide CDG on this issue seems to me to be the overriding priority. Clearly, as you proceed, you will need to have intimate discussions with Bill Wallenmeyer and Al Trivelpiece before a public decision.

Another point: I believe that we should use SSC in conjunction with other proposers of expensive facilities in a unified, pro-science campaign. "SCIENCE, the sinew of society, should not cringe! If this nation is ever to overcome its economic problems, it will be through a greater investment in science, etc., etc." I am enclosing an article from our British friends which makes sense. They say in effect, that at these prices, SSC must be sold for its potential economic benefits. We need to provide the leadership to pull all scientists together rather than have us fragment. One can use APS, NAS or whatever as vehicles for this effort.

Finally, in venting all this steam, there is another task that needs doing. In New York, California, Texas and numerous other places, there are very influential members of the industrial/financial community who think very positively about science and SSC -- even SSC as a man-on-the-moon-type of national goal. The challenge would be to call these people together in full view of our most influential policy makers to make their point.

Ed, if you work hard, you can get all these things done in the next few weeks and then go on a great holiday.

Sincerely,

Leon

Leon M. Lederman

Enclosure: Science Policy and Public Spending

cc: BoO
URA Trustees
J. Sandweiss (HEPAP)
J. Cronin (DPF)

APPENDIX 2

HIGH ENERGY PARTICLE PHYSICS

IN THE UNITED KINGDOM

Report of a Group Set up by the ABRC and the SERC to Review UK Participation in the Study of High Energy Particle Physics

Advisory Board for the Research Councils
Science and Engineering Research Council
June 1985

To Professor Sir David Phillips FRS 10 June 1985
Professor Sir John Kingman FRS

Dear David and John

HIGH ENERGY PARTICLE PHYSICS REVIEW

On behalf of the Group you appointed to review UK participation in high energy particle physics, I have pleasure in submitting our Report.

You will find a summary of the Report together with our recommendations in section H (page 87).

J C Kendrew

To Sir John Kendrew FRS 11 June 1985

Dear John

HIGH ENERGY PARTICLE PHYSICS REVIEW

Thank you for your letter of 10 June 1985 and the Report of the High Energy Particle Physics Review Group, which you chaired. We are most grateful for the considerable work that your group has done in producing this report. We have agreed that the Report should be published.

The Science and Engineering Research Council and the Advisory Board for the Research Councils will now consider the report and its conclusions and recommendations most carefully. We intend to provide advice to the Secretary of State for Education and Science in the Autumn of this year.

J F C Kingman
D C Phillips

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A INTRODUCTION

A.1. The joint review by the Advisory Board for the Research Councils (ABRC) and the Science and Engineering Research Council (SERC) into UK participation in High Energy Particle Physics (HEPP) research*, under the chairmanship of Sir John Kendrew, was announced to Parliament by the Secretary of State for Education and Science on 22 March 1984. At the same time the Secretary of State indicated that any proposal that affected the UK's relationship to CERN would be a matter for the Government, to be considered by due process and in consultation with other members of the Organization.

A.2. The agreed terms of reference for the review were:

"Having regard to the long-term health of British science and engineering research and to the Common Criteria for the support enunciated by the Advisory Board for the Research Councils in its second report 1974/75:

i. to review UK participation in the study of high energy particle physics, with particular reference to that necessarily carried out under international auspices;

ii. to consider possible future involvement, the role and extent of international collaboration, and the implications (including those for high energy particle physics in the UK, for other areas of British science and for international scientific co-operation in general) of reallocation of the resources in whole or in part to other areas of science;

iii. to report to the Chairman of the ABRC and the Chairman of the SERC".

---

*The term high energy particle physics requires a definition of the term "high energy", and this is at present commonly taken to imply values greater than about 1 GeV. For the most part studies of the nature of sub-atomic particles and of the forces between them involve the use of high energy accelerators, for the reasons explained in Section C. However, a few, but relatively cheap, experimental techniques do not involve accelerators and neither for these, nor for the theoretical aspects of the subject, is the term HEPP entirely appropriate. We have therefore used the term particle physics when discussing the subject as a whole and HEPP only when discussing accelerator-based experiments.

The membership of the review group is listed in Appendix 1 and a copy of the Common Criteria referred to in the terms of reference is included as Appendix 2.

A.3. The Review Group did not include a particle physicist in its membership, so Dr C H Llewellyn Smith FRS, a theoretical particle physicist from Oxford, was appointed as a consultant to the Group to brief the members on the subject and to explain technical issues; he did not, however, attend meetings at which evidence was evaluated or recommendations were formulated. The Group is much indebted to him for his help, as it is also to Mr J D Walsh of the SERC Central Office, who provided additional advice on his Council's support of particle physics and on the UK's membership of CERN. The Group also wishes to place on record the great debt it owes to its Secretary, Dr K D J Root of the DES, whose continued courtesy and diligence in arranging meetings, in obtaining and analysing data, and in drafting documents, have been essential to its work.

A.4. The Group has met 15 times to consider evidence and to prepare this Report. It has visited CERN and the Rutherford Appleton Laboratory, and met a representative sample of the UK HEPP community at a seminar at Imperial College of Science and Technology. Smaller groups of members have visited universities with varying degrees of involvement with particle physics, and the DESY laboratory in Hamburg. A full list of institutions visited by Members of the Group is given in Appendix 3 and we would like to express our thanks to all those involved with the arrangements.

A.5. The Group received oral evidence from those listed in Appendix 4, which includes scientists with research interests in particle physics and related fields, other scientists, representatives of the Committee of Vice Chancellors and Principals (CVCP) and the Heads of Research Councils. It also invited written evidence from individuals and issued an open invitation for written submissions through a press notice of 24 May 1984. Those responding are listed in Appendix 5. Professor Dowell, the Chairman of the Particle Physics Committee, organized an ad hoc group to prepare a number of papers, which are listed in Appendix 6. Also listed in that appendix are the titles of the papers submitted by other bodies including the CBI, the CVCP and the Royal Society, and of published documents considered by the Group.

A.6. Any examination of possible changes in the UK's involvement with HEPP requires a consideration of the implications for international scientific co-operation in general and we record our views on the growing importance of international collaboration in all areas of scientific research at the end of Section B. We are also aware that there are wider foreign policy implications, but these have not been considered in any detail by the Group.

A.7. From the evidence that we have received it is clear that members of the public, and even scientists outside the field, are not well informed about the aims of particle physics. We have therefore included in section C a brief survey of this field drafted by Dr Llewellyn Smith. There is also a widely held view that the cost of the subject has been continually increasing, with each new accelerator significantly more expensive than the last, whereas, in fact, the proportion of the SERC budget devoted to particle physics has fallen over the past decade from 33% in 1975/76 to the present figure of 20%. Nevertheless this is still a substantial proportion to be allocated to one area of physics and would need justification. Again, the cost of the new accelerator at CERN (LEP) is expected to cost less than the previous one (SPS), but with a materials cost of about £350M this is still a major investment for European science. The costs of all aspects of UK expenditure on HEPP are recorded in sections E and F.

A.8. Our terms of reference required us to consider UK participation in HEPP in the context of UK science as a whole. This involved an examination both of the relevance of HEPP to the rest of UK science, and of possible alternative uses of the funds at present used to support HEPP (i.e. its opportunity cost), within the context of subjects covered by the DES science budget. It was impossible to carry out the latter task in the same depth as our examination of high energy particle physics itself, and therefore we attempted only to obtain an overview of the situation rather than looking at any area in detail; our findings are reported in section G.

A.9. The final section of this Report records the Group's views on present levels of expenditure on HEPP and summarizes its recommendations.

B. BACKGROUND TO THE FUNDING OF SCIENTIFIC RESEARCH THROUGH THE RESEARCH COUNCILS

GENERAL ECONOMIC BACKGROUND.

B.1. The pursuit of scientific research embraces a complex set of human activities and aspirations. At one extreme it is an expression of curiosity about the very odd universe presented to our view - devoid of any expectation of economic benefit. At the other, it is a deliberate application of scientific knowledge and methods to the development of useful application. It is customary to talk about "pure" and "applied" science, but in practice these terms are of rather little help in attempting the segmentation of the total field of scientific activity, and this for two reasons. The first is that utility can flow from the purest of scientific endeavours, wholly innocent of any desire to seek applications. The second is almost the inverse proposition; that radically new perceptions and understanding - "pure" scientific results - can arise from the endeavours of scientists and engineers whose interests at the time of the discovery were wholly directed towards clearly defined applications.

B.2. Any number of examples can be cited to illustrate the connection between pure science and the emergence, sometimes many years later, of useful applications. Arguably, most of the key technologies that have transformed industry and society came about by this route. The discovery of nuclear fission is an example which is often cited as the direct result of the nuclear physics of the thirties. A single example of the reverse process may suffice - the discovery of holography, which arose through the very practical desire to reduce the aberrations of electron microscopes, but which has none the less all the hallmarks of a quite fundamental advance in science.

B.3. The strong connection between the "pure" and the "applied" militates against any simplistic formulation of science policy. The problem is exacerbated by the delay between a discovery and the possible emergence of utility. It can be very short, for example, less than a decade between the discovery of fission and the demonstration of the first nuclear reactor. Or it can be long, for example, the interval between the discovery of fusion and the demonstration of the first fusion reactor which, even in a sub-economic phase, is likely to exceed half a century. Yet the difficulty of making predictive judgements does not, in our view, amount to a denial of the need for policy. There is no question that it is essential to derive a substantial measure of utility from the scientific research conducted in the UK and elsewhere.

B.4. Since the late 1970s, part of the UK's imports has been paid for by exports of North Sea oil. By the end of the century, output of North Sea oil will decline. It is therefore essential that industry should be dynamic and competitive enough to develop new markets and products on a sufficient scale to replace the decreasing contribution of oil to the balance of payments. This switch will have to be made in the face of the continuing industrial development of competing nations - not least Japan and other newly industrialized countries in the Far East.

B.5. We believe that the next phase of manufacturing development will rely predominantly on the creation of science-based industries - embracing, inter alia, the newest capabilities in information technology and biotechnology. The chances of creating the requisite additional industrial capability must depend to a large extent on the vitality of UK scientific research and of the scientific community. In spite of the above-mentioned difficulties in assessing the utility likely to flow from different forms of scientific endeavour, it is clearly vital that the effort be made. Nor do we regard the attempt as hopeless - provided it is appreciated that the assessments are of necessity probabilistic. For example, we believe that it is not meaningless to assert that research on black holes is less likely to provide utility by the turn of the century than research on self-organizing systems. Yet both are evidently "pure" research. Success in either can make a contribution to the pursuit of science.

B.6. In attempting to delineate some rational division of resources amongst the very wide range of activities that make up the research world, it is also important to appreciate the existence of a spectrum of motivations. At its "pure" end the aim is to carry out research that will significantly add to the sum of human knowledge about the universe, with an inevitable and wholly appropriate emphasis on priority of discovery. At its "applied" end the aim is more usually to strive for an overall success in achieving an applicable result which may be the summation of many individual creative steps, no one of which in itself justifies the cry of Eureka!

B.7. The advice that we have been asked to tender on the future funding of HEPP must, we feel, be made in the light of these considerations, and most emphatically against a background of the current and anticipated strength of the UK economy. We appreciate that the progress of science depends on individual acts of creativity, so it is necessary that any system of support for science must make it possible for creative scientists to be given scope to exploit their ideas. Nevertheless surveying the scientific scene in this Country, we believe that a greater degree of concentration of resources is needed. We also believe that selection should take into account both the excellence of the science and its likely utility, and that even within basic science there should be some further redistribution of resources towards projects with a higher probability of early application.

THE DES SCIENCE BUDGET

B.8. Paragraph 33 of the ABRC's 1983 forward look, which was included as section G of its report "Scientific Opportunities and the Science Budget 1983" (ref 1) commented on the size of the Science Budget and indicated that for the last 10 years it had remained broadly constant when expressed as a proportion of the GNP. Furthermore, up to 1983 the real level of the Research Councils' income had also remained fairly constant, but despite this the volume of resources available for basic research had fallen substantially.

B.9. A number of reasons for this fall were identified in the report, including the following:

1. the UGC support for universities had fallen by 11% and there was evidence that cuts had fallen disproportionately on university research; the "well found laboratory" could no longer be assumed by the Research Councils;

ii. following the Rothschild Report in 1971 (ref 2), there had been a transfer of funds from the Science budget to Government departments responsible for various areas of research, which then commissioned research from the Research Councils, mainly AFRC and NERC, which undertook much of their research within their own institutes; the recent reductions in commissioned research have led to significant restructuring costs, which have fallen on the Science budget and hence, in the short term, have further reduced the funds available for science;

iii. The cost of the infrastructure of research has increased considerably faster than the general inflation rate, especially in the area of general laboratory equipment (the so called "sophistication factor").

These factors, coupled with the failure of the Treasury to compensate fully for the increasing costs of subscriptions for international facilities due to external factors such as the fall in the value of sterling, have led to prognostications by the Chairman of the ABRC that under present Government policies there will be a 25% cut in support for science in real terms over the next 10 years. The situation has been slightly ameliorated by the additional funds secured for the Science Budget for 1985/86, 1986/87 and 1987/88, but these will only enable it to keep up with general inflation.

B.10. The present shortfall in resources for science and the fear of this trend continuing led the ABRC to propose to the Secretary of State that it should consider the implications of withdrawing from high energy particle physics research, in order to release funds to provide more adequate support of existing top priority research in other areas of science, and to enable it to respond to new scientific challenges.

B.11. If the Science budget were to decrease in real terms by 25% over the next 10 years through under-indexation etc., there would clearly come a time when, no matter how high a value was placed on an expensive area of research, the present level of expenditure on it could not be justified. However, we have taken as a basis for our consideration of the UK's participation in particle physics that the science budget will be properly adjusted to cover the effects of general inflation and of changes in international subscriptions due to relative changes in GNP and exchange variations.

INTERNATIONAL COLLABORATION

B.12. There is a long tradition that science is an international activity, undertaken by scientists from many countries. Communication has been ensured by frequent international conferences and symposia and by the open publication of scientific results; international collaboration has been fostered by the virtually universal practice of welcoming scientists from abroad to work for short or long periods in the laboratories of every country.

B.13. In some areas of science more formal international collaborative ventures have been organized. Some of these, like CERN, involve setting up an international laboratory by inter-governmental agreement. Such international organizations are usually proposed when the research involves facilities too expensive for one country to afford alone or when the participating countries consider that a joint research programme should be undertaken to enhance the activity in a particular field. Examples of such collaborative organizations and their cost to the UK Science budget in 1984/85 are:

CERN	£35.7M
European Space Agency (Science programme)	£12.0M
Institute Laue-Langevin (high flux neutron source)	£ 7.0M
European Molecular Biology Laboratory	£1.6M
Anglo-Australian Telescope	£1.1M
European Incoherent Scatter Facility	£0.35M

B.14. In recent years an alternative method of organizing international collaborative ventures has been for one country to take the lead in setting up a national facility, and then to invite partners from other countries to contribute to the cost of the central facilities or to their exploitation. Overall control of the facility is retained by the host country, but there is usually a mechanism by which the partners can offer advice on the experimental programme. Examples of such internationalized national facilities are the DESY high energy laboratory at Hamburg and the optical telescopes at La Palma. It is also hoped to obtain more substantial international collaboration for the Spallation Neutron Source at the Rutherford Appleton Laboratory.

B.15. In our view there will be an increasing need for international collaboration as the supporting facilities required for many branches of science become more and more expensive. We are also agreed that international collaboration has scientific and cultural benefits which complement the financial issues. However, control of international activities presents various difficulties and the need for salaries adequate to attract staff to work abroad often increases the cost. A great deal of vigilance has to be exercised to ensure that the organization is efficient and that it provides the most appropriate facilities for the scientists of member states.

B.16. The importance that we attach to international collaboration and to the need for trust between countries going beyond the minimum legal requirements of international treaties has led us to take it as a boundary condition that, for the reasons explained in paragraph H.6(iii), the UK could not reasonably withdraw from CERN membership before the end of the construction of the new machine (LEP) at CERN, i.e. before December 1989, whatever recommendations we might make for the longer term future.

C. HIGH ENERGY PARTICLE PHYSICS

THE AIMS OF PARTICLE PHYSICS

C.1. Particle Physics is the study of the basic constituents of matter and the forces that act between them.

C.2. The study of basic constituents is the natural continuation of research that led to the discovery of the atom, the electron, the atomic nucleus and the proton and neutron. In the last fifteen years, it has become firmly established that protons and neutrons, and the large number of related nuclear particles, are all made of a small number of more elementary entities called quarks. These quarks, like the small number of non-nuclear particles such as the electron and the neutrino, behave as structureless point-like particles at the present level of measurement (down to 10^{-18} m or 10^{-3} of the size of the proton).

C.3. The study of forces is the natural continuation of Newton and Einstein's work on gravity, of Faraday and Maxwell's unification of electricity, magnetism and light, and of Dirac's work on quantum electrodynamics which describes electric forces in terms of the "exchange" of quanta, or particles, of light called photons. In the last ten years the existence of a particle known as the gluon, the exchange of which generates the strong interquark force, has been established by experiments at DESY in Hamburg. The W and Z particles, the exchange of which generates the weak force which is responsible for radioactive decay and which controls the energy cycle in the sun, were discovered at CERN in 1983. Their properties confirm the earlier speculation that although weak and electromagnetic effects are very different, they are actually different manifestations of a single unified "electroweak" force.

C.4. Particles may be divided into "force carriers" (the photon, the gluon, the W and Z, and the graviton, the hypothetical carrier of gravity) and "constituents of matter". The latter comprise nuclear particles, which are made of quarks, and non-nuclear particles, such as the electron, which are known generically as leptons.

At present six leptons and six quarks are known. The electroweak theory requires the numbers of quarks and leptons to be equal, but it does not determine their total number nor does it explain their different masses. According to some speculative theories, quarks and leptons are closely related while being elementary; another possibility is that they will turn out to be composite, possibly sharing common constituents. In order to settle such issues, it is necessary to study the properties of quarks and leptons in greater detail, to search for possible sub-structure at smaller distances, and to discover whether any more quarks and leptons exist.

C.5. The basic laws which govern the strong interquark force and, in principle, determine the properties of nuclear particles, are now known; the theory which describes them is known as Quantum Chromodynamics or QCD. However, only a few of these properties can at present be derived in detail from QCD; even the widely held belief that the strong force is so powerful that quarks and gluons cannot exist as individual particles, but always bind together in certain specific combinations, has not been rigorously proved. Theoretical understanding of the strong force is growing, helped by a remarkable formal similarity to problems in condensed matter physics, which has produced a mutually beneficial cross-fertilization (e.g., ideas developed originally in the context of particle physics have been crucial for breakthroughs in understanding phase transitions). However, complete understanding will require further experimental information, for example, an answer to the question whether there exist nuclear particles composed solely of gluons with no quarks.

C.6. The basic laws which govern the electroweak force are now probably known, although crucial experiments remain to be done before this can be accepted as fully established. However, the origin of the large mass difference between the carriers of the weak force, the W and Z whose masses are about 100 times that of the proton, and the carrier of the electromagnetic force, the massless photon, is not understood (it is this large mass difference which hides the underlying connection between electromagnetic and weak forces). The origin of the masses of the W and Z is probably closely connected with the origin of the masses of quarks and leptons. Various theoretical mechanisms have been proposed to account for the observed masses. All of these predict new phenomena; for example, one mechanism predicts the existence of a new particle known as the

Higgs boson. These phenomena are expected to appear at energies related to the masses of the W and Z. The next generation of experiments will explore these energies and may therefore cast light on the very basic question of the origin of mass.

C.7. There are striking mathematical similarities between the theories of the strong force, the electroweak force and the gravitational force, the latter being the only other force known; all are based on a principle known as local gauge invariance. The similarities encourage speculation that these forces are in fact different manifestations of a single unified force. Consistent "grand unified" theories of strong and electroweak forces can now be constructed, in which there is no fundamental distinction between the strong nuclear force and the electroweak force. It is perhaps not surprising that there is then no fundamental distinction between nuclear particles (quarks) and non-nuclear particles (leptons) and that, according to grand unified theories, protons can decay. Experiments are under way, in deep mines sheltered from some of the effects of cosmic radiation, to test this speculation. Proton instability would have important cosmological implications. Indeed grand unified or other theories that are capable of describing particle interactions at the energies available just after the "big bang" are crucial for any discussion of the early evolution of the universe. Conversely, the cosmos may provide an indirect testing ground for such theories.

C.8. The above discussion of fundamental questions (the nature of quarks and leptons, the origin of mass, further unification of forces) has necessarily been in the framework of existing knowledge and current theories. The next generation of experiments will study particle collisions at energies ten times greater than those available hitherto. Past experience suggests that, in addition to providing answers to some of the questions posed in advance, the exploration of a new energy domain will yield surprising and exciting discoveries.

EXPERIMENTAL METHODS AND FACILITIES

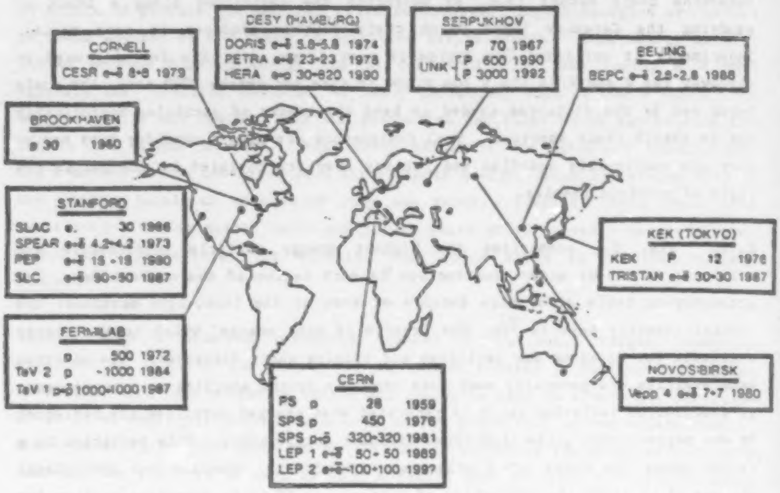
C.9. The main tools of particle physics are the accelerators used to produce beams of high energy particles. High energy particles have the short quantum-mechanical wavelengths needed to resolve the structure of matter on a small scale. The energy of the particles available in the 1940s was sufficient to resolve protons and neutrons inside the nucleus; by the late 1960s the quark structure of protons and neutrons could be resolved; higher energies are needed to learn whether or not there is structure inside quarks. High energy is also needed because kinetic energy can be converted into mass (using $E = Mc^2$) allowing the creation and study of heavy particles, such as the W and Z, the heavier quarks and leptons, and the postulated particles which may provide the key to the origin of mass. Such heavy particles are generally short-lived; their masses can be converted back into kinetic energy, which is carried away by the lighter particles into which they may decay. However, there could also exist long-lived or stable heavy particles, which would probably have important practical applications; for example, they could serve to catalyse nuclear fusion.

C.10. When a beam of particles strikes a stationary target, momentum conservation requires the debris to be thrown forward. The kinetic energy associated with this motion is wasted and cannot be used to create new particles or to probe short distances; the useful energy grows only as the square root of the beam energy. This waste can be avoided by colliding two beams of particles head-on. The price to be paid is that a second beam provides a much less dense target than a stationary piece of matter. Furthermore, only stable charged particles (protons, antiprotons, electrons and antielectrons or positrons) can be stored and collided head-on, whereas collisions with a fixed target can be used as a source of secondary beams of transient and/or neutral particles, such as pi mesons or neutrinos, whose interactions can then be studied. Nevertheless, most future experiments will involve colliders because of the huge energy gain. For example, in order to produce the same useful energy as the CERN proton-antiproton collider (used to discover the W and Z) a beam with 300 times the combined energy of the colliding beams would be needed in an experiment with a fixed target.

C.11. Experiments at accelerators and colliders are performed by surrounding the collision point with large systems of detectors. These sophisticated devices are designed to detect the particles which are produced (e.g. by detecting the ionization generated along the tracks of charged particles, or the secondary particles produced by the interactions of neutral particles), to measure their energies and momenta (e.g. by measuring the total ionization produced, or studying how their tracks are bent in a magnetic field) and to determine their nature (e.g. by measuring the ionization along a track or studying the Cerenkov light which their passage produces in some media). Experiments at colliders are typically very large, e.g. the detector used to discover the W and Z is 10m x 10m x 10m in size and weighs 2000 tons, the scale being set by the distances needed to bend the tracks of particles magnetically and to absorb their energies. Such instruments are always used for many years; they are continually modified and the way they are operated is changed in the light of previous results.

C.12. Fig. C.1 summarizes the highest energy particle accelerators and colliders in use or under construction in each region of the world today. The accompanying table gives more details of some of the front-line machines: the crucial quantity here is E_{cm}, the "centre of mass energy" which is the energy available for creating new particles and probing short distances. The electron beam energies are generally much less than the proton energies as a consequence of synchrotron radiation which is generated when charged particles are deflected by the magnets that guide them round circular accelerators. This radiation is a useful bonus for those other scientists (physicists, chemists and biologists) who use it to study the properties of matter, but it is an expensive problem for particle physicists. To reduce the energy lost by radiation, circular electron machines must be made very large and this proves to be the limiting cost factor (above about 150 GeV per beam, linear colliders may be cheaper: see paragraph C.18). Synchrotron radiation is unimportant for protons because they are so much heavier, which is why they can then be accelerated to much higher energy than electrons for a comparable cost (the limiting factor for proton accelerators is the maximum strength of the magnetic field that bends the beam, which determines the radius of the machine). Nevertheless, electron machines are able to hold their own because, in a proton machine, the energy of the proton is shared among a cluster of quarks and gluons so that an individual quark or gluon typically carries only one tenth to one fifth of the beam energy. Moreover, the interpretation of proton collisions is complicated by the fact that the fraction of energy carried by an individual quark or gluon is not fixed.

C.13. Different types of accelerator act as complementary "microscopes" to probe the quarks and leptons, and to search for new clues to the nature of the


THE WORLD OF HIGH ENERGY ACCELERATORS

CORNELL
CESR e-ē 8-8 1979
DESY (HAMBURG)
DORIS e-ē 5.6-5.6 1974
PETRA e-ē 23-23 1978
HERA e-p 30-820 1990
SERPUKHOV
P 70 1967
UNK P 600 1990
P 3000 1992
BEIJING
BEPC e-ē 2.8-2.8 1988
BROOKHAVEN
p 30 1960
STANFORD
SLAC e. 30 1966
SPEAR e-ē 4.2-4.2 1973
PEP e-ē 15 - 15 1980
SLC e-ē 50-50 1987
KEK (TOKYO)
KEK P 12 1976
TRISTAN e-ē 30-30 1987
FERMILAB
p 500 1972
TeV 2 p ~1000 1984
TeV 1 p-p̄ 1000-1000 1987
CERN
PS p 28 1959
SPS p 450 1976
SPS p-p̄ 320-320 1981
LEP 1 e-ē 50 - 50 1989
LEP 2 e-ē ~100-100 199?
NOVOSIBIRSK
Vepp 4 e-ē 7-7 1980

FIG. C.I

The acronym for each accelerator is followed by the type of particle accelerated (proton (p), antiproton ($\bar{p}$), electron (e) and positron ($\bar{e}$)), the energy in GeV of the particle beam or beams, and the date of completion or expected completion. The table below gives further details of some of the front-line machines, including the centre of mass energy (E_{cm}), which is the useful energy available for creating new particles. 1 GeV is slightly more than the energy required in principle to create a proton at rest (0.94 GeV)

SOME MAJOR FACILITIES

		Existing	Under Construction
EUROPE	CERN	SPS 450 GeV p E_{cm} 30 GeV	LEP (1989) 50 GeV e + 50 GeV $\bar{e}$ E_{cm} 100 GeV (E_{cm} 200 GeV 1992?)
		$Sp\bar{p}S$ 320 GeV p + 320 GeV $\bar{p}$ E_{cm} 640 GeV	
	DESY	PETRA 23 GeV e + 23 GeV $\bar{e}$ E_{cm} 46 GeV	HERA (1990) 30 GeV e + 820 GeV p E_{cm} 315 GeV
USA	FNAL	Tevatron 800 GeV p E_{cm} 40 GeV	Tev 1 (1986) 1000 GeV p + 1000 GeV $\bar{p}$ E_{cm} 2000 GeV
	SLAC	PEP 15 GeV e + 15 GeV $\bar{e}$ E_{cm} 30 GeV	SLC (1987) 50 GeV e + 50 GeV $\bar{e}$ E_{cm} 100 GeV

forces and the origin of mass. Very crudely, proton-proton (pp) and proton-antiproton ($p\bar{p}$) colliders reach the highest energy but, for most purposes, are relatively blunt exploratory instruments compared to electron-positron ($e\bar{e}$) and electron-proton (ep) colliders. For example, while pp collisions yield some information about how the energy is shared between the quarks and gluons in the proton, this is crude compared to what can be learned from ep collisions. Similarly, although the Z and (probably) the sixth quark have been discovered at a $p\bar{p}$ collider, investigation of their detailed properties must await the $e\bar{e}$ colliders, SLC at Stanford and LEP at CERN. However, pp and $p\bar{p}$ colliders are not best suited to discovering new leptons, for which $e\bar{e}$ colliders are supreme. To study all combinations of lepton, quark and gluon interactions, it is clear that $e\bar{e}$, ep and pp or $p\bar{p}$ colliders are needed. A balanced programme requires access to different types of colliders with their complementary virtues, as well as certain non-accelerator experiments, such as proton decay experiments.

EXPERIMENTAL OPPORTUNITIES: THE NEXT DECADE

C.14. Probably the most exciting experiments underway at present are those at the CERN $p\bar{p}$ collider. This spring, at the suggestion of a group from Cambridge, the collider is being run in a special mode which allows a much higher energy (E_{cm} = 900 GeV) to be reached at the price of lowering the mean intensity. The immediate aim of the collider experiments is to search for new phenomena and to study the properties of the W and Z and of the sixth quark. Recently a few examples have been observed of collisions in which a collimated jet of energetic particles is produced, unaccompanied by any visible particles moving in the opposite direction carrying the balancing momentum. It is hard to understand these "monojets" in terms of QCD and the standard electroweak theory, although it is too soon to be sure that it is impossible. One exciting speculation is that they are due to the production and decay of a new sort of "supersymmetric" quark or gluon, much of whose energy goes into a neutral particle which leaves no track. "Supersymmetric" quarks, leptons, gluons, W's and Z's are predicted in an elegant class of theories which help in understanding the masses of the W and Z, and provide a natural framework for unifying gravity with the other forces.

C.15. At Fermilab in the USA the Tevatron is now operating at 800 GeV, allowing detailed "fixed target" experiments at a centre of mass energy 25% higher than previously available. The Tevatron will start to operate as a $p\bar{p}$ collider at the end of next year at energies which may eventually go up to 2000 GeV. The CERN $p\bar{p}$ collider should nevertheless remain competitive for some time because it is being upgraded to increase the intensity and because both the machine and the experiments, which are being improved, are well run-in.

C.16. The $e\bar{e}$ colliders SLC and LEP should start to produce data in 1987 and 1989 respectively. These machines can be tuned to the rest energy (Mc^2) of the Z. When the colliding electrons and positrons meet and annihilate, the Z boson will be produced directly at a much higher rate than in $p\bar{p}$ collisions. The SLC is a new sort of machine (C.18) and it is very hard to predict how quickly it can be brought into operation and how well it will work. The CERN $p\bar{p}$ experiments have so far detected about fifty Z's. The SLC experiment should initially be able to study tens of thousands of Z's per year and with luck the rate will be much higher. Each of the four LEP experiments will study millions of Z's per year. These experiments will lead to the discovery of any new quarks and leptons (including supersymmetric quarks and leptons) into which the Z can decay, they will provide a good way to search for the new particles whose existence is predicted by theories which account for the masses of the W and Z, and they will provide new insights into details of the electroweak force and the strong force.

C.17. The declared purpose of LEP is not only to study the Z but to go well beyond it in energy. The size of the machine was chosen so that it can be upgraded to 100 GeV per beam or more; this can be done gradually by adding superconducting radiofrequency cavities, and it now seems that 90 GeV/beam can be reached relatively easily in this way at a total cost of about 175 million Swiss francs. LEP was deliberately designed to reach such energies because they are needed to study the production of a pair of W bosons, which would allow tests of basic, but hitherto untested, features of the electroweak theory and could be vital in unravelling the origin of the masses of the W and Z. In addition, an upgraded LEP would have a unique capability to extend the search for new quarks, leptons and other particles by a factor of two in mass.

C.18. SLC is designed as a "machine experiment" to test some of the principles involved in constructing linear colliders, in which electron and positron beams from two opposed linear accelerators would be collided. Such machines are expected to become cheaper than circular machines for energies above about 150 GeV per beam (C.12). SLC will actually use a single accelerator to produce both beams, which will then be separated and collided (the use of the existing SLAC linear accelerator makes the project economically feasible). Since the beams are then lost, a reasonable collision rate can be achieved only by focusing them to about one micrometre in diameter. Producing and colliding such beams is a formidable challenge. As well as testing the concept of linear colliders, SLC will allow the first detailed study of the Z. Some trepidation has been expressed that this will reduce the initial interest of the LEP experiments. Whether or not SLC will steal some of LEP's thunder depends on unpredictable technical issues (how well SLC will work) and unknown physics (what surprises are in store in Z decay and how easy it is to discover them). In any event, LEP experiments should eventually provide definitive high-statistics studies of the Z, and only (upgraded) LEP can explore the region well beyond the Z in energy.

C.19. The ep collider HERA will come into operation at DESY in 1990. HERA has excited great interest in the UK because it allows a natural continuation of studies of the structure of the proton, in which UK physicists have played a prominent role. HERA experiments will probe the structure of the proton and of the quarks within it at distances ten times smaller than those reached so far. They will also give new insights into the strong and weak forces, complementary to those provided by LEP and SLC. Because the electron beam in HERA will be polarized the experiments will provide a unique probe of the weak interactions of electrons and quarks.

C.20. The preceding discussion has focused on opportunities which will be provided by major new facilities, especially colliders. There will be opportunities as well to search for proton decay in existing and new underground experiments, which are also sensitive to any powerful cosmic sources of neutrinos and to any new highly penetrating particles that might be present in cosmic rays. Furthermore there will, of course, be continuing opportunities to perform fixed target experiments at existing accelerators. These experiments will allow detailed studies of many interesting phenomena which can probably be understood in terms of known laws (e.g. the recent discovery by the European Muon Collaboration group at CERN that quarks do not behave in the same way in nuclei as they do in free protons and neutrons) and they may help in answering questions such as whether there exist particles composed primarily of gluons (experiments at the low energy antiproton facility LEAR at CERN will address this question). Furthermore, there are still important questions of principle which may be answered by precision low energy fixed target experiments, e.g. the origin of the very small difference between the behaviour of matter and antimatter (an effect known as CP violation) and the question whether neutrinos behave in ways which require them to have small masses, which would have important astrophysical and cosmological implications.

EXPERIMENTAL POSSIBILITIES: THE LONG-TERM FUTURE

C.21. With the Fermilab $p\bar{p}$ collider, SLC, LEP and HERA all under construction there is a rich experimental programme ahead. Nevertheless, it would be unrealistic to think that experiments at these facilities will answer all questions and particle physicists are therefore looking ahead to what might follow. In Europe the present healthy programme will last until the middle to late 1990's, assuming that LEP is completed by upgrading the energy; detailed long term planning is therefore not urgent, although some forethought is needed as a guide to research and development on magnets and accelerating systems. In the USA, however, the particle physicists consider that, if they wish to maintain a programme at the forefront of the subject, they must initiate a new project soon.

C.22. It is hard to anticipate what machine will seem most desirable following full results from the $p\bar{p}$ colliders and data from SLC, LEP and HERA. In the past a jump of an order of magnitude in centre of mass energy has generally been sufficient to guarantee significant progress: rather general arguments suggest that, with such an energy jump, experiments at either an $e\bar{e}$ or pp collider could definitively discriminate between different theories of the origin of mass, if this issue has not already been settled. However, it is not sensible to propose an $e\bar{e}$ collider with energy significantly higher than that of LEP pending a demonstration by SLC that linear colliders work, and even then several years research and development of accelerating systems will be needed in order to show that intense beams with energies of several hundred GeV can be produced economically. Proposals for future machines are therefore limited to pp or $p\bar{p}$ colliders at present.

C.23. Particle physicists in the USA have united behind a proposal to construct a Superconducting Super Collider (SSC), a proton-proton collider with an energy of up to 20,000 GeV per beam. Preliminary studies put the construction cost at about 3 billion (1984) dollars. Further design studies are under way, but it is unclear whether this project will be approved. The SSC could, in principle, be operational ten years from now if it were approved in the very near future.

C.24. Preliminary studies at CERN have shown that a proton collider, dubbed LHC for Large Hadron Collider, with an energy of 6,000 GeV per beam, could be built in the LEP tunnel with existing technology for much the same price as the LEP project. It seems likely that, with further research and development on superconducting magnets, the energy could be increased substantially, perhaps to 9,000 GeV per beam. The potential of a collider does not increase linearly with energy, and a 6000 GeV machine would look into roughly half of the "physics window" open to SSC, albeit with less effective intensity or "luminosity", whereas a 9000 GeV machine would see roughly two-thirds of the window. Comparison of SSC and LHC depends on whether or not there is qualitatively new physics which would only be visible through the SSC's larger and brighter window. An LHC beam could be collided with one of the LEP beams to produce ep collisions with a centre of mass energy six times that which will be available at HERA.

C.25. Most particle physicists accept that it is unrealistic to expect that similar large machines will ever again be constructed simultaneously in different geographical regions, and that all future plans should therefore be considered in a global context. An obvious possibility would be to pool resources to construct a single world laboratory. Apart from practical difficulties, this would not be scientifically desirable because a single laboratory would not provide a balanced programme (unless it housed several different machines) and the mechanism for choosing priorities might be too monolithic. A better plan would be to provide complementary machines in different regions, to which physicists from other regions would have access.

This effectively describes the present situation, in which the large laboratories in W. Europe and the USA follow an open-door policy, described in guidelines laid down by the International Committee for Future Accelerators (ICFA) to which they subscribe. There is currently large, and approximately balanced, cross-utilization of facilities in Europe and the USA. Furthermore, there are user groups from the USSR, Japan and other countries at CERN, DESY, Fermilab and SLAC, who provide experimental apparatus for the collaborations to which they belong, and groups from W. Europe have worked in the USSR, through an agreement between CERN and the Serpukhov laboratory.

C.26. In the short term, global planning for high energy physics depends on whether the SSC is approved. In the medium term, it depends on whether linear e^+e^- colliders turn out to be practicable. In the long term, it depends on progress in developing new accelerating techniques. In the last two decades, costs have been contained by advances in technology and by re-using existing components; these factors account for the fact that LEP is cheaper than the SPS and that an LHC might cost no more than LEP. In the future, however, costs are likely to grow (viz. estimates that large linear e^+e^- colliders are likely to cost billions of dollars) unless new techniques are introduced. The key to building large linear e^+e^- or pp colliders is the development of high accelerating gradients and efficient methods of transferring power to the beams. Various ideas are being studied, e.g. wake field accelerators in which electric fields produced by the passage of one very intense beam are used to accelerate particles in a second parallel moving beam, and various ways of exploiting the very high transverse electric fields in laser beams, for example by exciting "beat" waves in a plasma in which the charge separation then generates a longitudinal electric field. It would be unrealistic to think that the cost of building and operating very high energy accelerators will decrease dramatically as a result of this research but, in the long term, it may make it possible to go to much higher energies, beyond upgraded LEP, LHC and SSC, without large increases in cost.

D. THE RELEVANCE OF PARTICLE PHYSICS TO OTHER SCIENCES AND TO TECHNOLOGY

D.1 The discovery, in the early years of this century, of the nature and structure of atoms has transformed both science and society. It has led to an understanding of basic physical laws and has, with remarkable rapidity, produced a rich range of applications over the years, of which more recent examples are solid state devices, nuclear energy, genetic engineering and information technology. Indeed it is hard to identify any of the new technologies of our time of which the root cannot be traced back to fundamental discoveries in atomic and nuclear physics.

D.2 The quest for a deeper understanding of the nature of matter - the main theme of particle physics - is rightly seen as an extrapolation of the research that earlier in the century uncovered the structure of the atom and later of the nucleus.. A recent spectacular development in particle physics, which has led to the unification of the electromagnetic and the weak force, inspires hope that we may yet discover the 'philosopher's stone' in a grand unification of all the four forces, whereby all that there is could then be attributed to the action of one single law of nature. No one who has any acquaintance with this field of science can see it as other than enormously exciting, exhilarating and intellectually rewarding.

D.3 The search for the ultimate laws of matter is surely a 'fundamental' area of science, but we would not support the contention of some witnesses that particle physics should be regarded the most fundamental study imaginable. Rather we agree with the view taken by Feynman in 'The Character of Physical Law' that the fabric of science is a 'net' in which every part is interconnected with every other part, but where no scientific discovery is accorded a position of unique significance. From this point of view, the discovery of the W particle is no more (and no less) 'fundamental' than the discovery of the structure of DNA.

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D.4 On the other hand, some witnesses have suggested that particle physics is an isolated discipline which has little relevance to other areas of science. We have therefore examined the relationship of particle physics to other subjects in some detail, by discussing it with scientists in related fields, and we have also received written evidence on this issue, including a paper from the Particle Physics Committee.

D.5 Deriving from common origins, nuclear structure physics and particle physics have diverged from each other over the past four decades, but recent developments have now shown that there are important interrelations. For example, the assumption that, to a first approximation, the internal structure of protons and neutrons can be ignored in nuclear structure work has been challenged by the results obtained by the European Muon Collaboration at CERN. These results have shown that the behaviour of quarks in neutrons and protons depends on whether these nucleons are free or bound in nuclei and this phenomenon (now known as the EMC effect) could have a profound influence on the future of nuclear structure physics. Although EMC is completing its work prematurely because of the withdrawal of the UK contribution, due to cuts in the particle physics budget, some nuclear structure physicists are proposing to use the same apparatus at CERN to take forward the work. Nuclear structure physicists are also proposing to use the SPS collider at CERN for high energy collisions of ions.

D.6. Cosmic ray physics has always been closely related to particle physics and provided the first source of unstable particles. As accelerators increased in energy, particle physics became less dependent on cosmic ray work, but in turn the detectors developed for accelerators became available for cosmic ray experiments. Similarly, the large experimental devices being used to search for proton decay can also be used to detect cosmic ray muons and neutrinos, and hence have potential to make a significant contribution to astrophysics. Expertise in particle physics is also of use in interpreting the extensive cascades produced in the atmosphere by the highest energy cosmic rays and thus contributes to the understanding of the nature and origin of these particles.

D.7. The current interest of cosmologists in particle physics developments is a timely reminder of the breadth of fundamental science and of the ways - often unexpected - in which the different disciplines interact and influence each other. The matter which is visible in the form of galaxies, stars and planets is believed to have arisen from a small excess of matter over anti-matter in the very early universe. An explanation of this excess offered by current theory leads to the prediction of a very long, but finite, lifetime for the ubiquitous proton. Particle physicists are now actively searching for evidence of proton decay (C.7).

D.8. The answer to the related (and awesome) question how the universe came to be as it is, depends on the form in which most of the mass may be hidden. One possibility is that vast numbers of neutrinos, of small but non-zero mass, may relegate the visible (baryon) matter to the status of a minor constituent of the universe. Again, the crucial measurement is awaited from current particle physics experiments. An alternative explanation for the form of the universe, which would also reduce the baryon matter to a minor role, is that new and as yet undetected particles, predicted by current 'gauge' theories, such as the photino, gravitino and axion, actually dominate the mass distribution and hence have determined the formation of the galaxies and the large-scale structure of the universe that we now see. Clarification of these ideas is eagerly awaited both by particle physicists and by cosmologists, as well as by the wider lay audience that remains fascinated by these major astrophysical questions.

D.9. The relation between theoretical particle physics and condensed matter theory was mentioned in paragraph C.5, and we have been told that some of the leading condensed matter theoreticians were originally trained in particle physics. Examples of techniques developed in particle physics that have found major application in condensed matter physics include Feynman diagrams and the renormalization group; the latter is the basis for recent advances in understanding of phase transitions. On the other hand, the development of the idea of spontaneous symmetry-breaking, which explains why the pi meson is light and why the W and Z may be heavy (as they have proved to be), was strongly influenced by work on superconductors. We discuss later some techniques developed by particle physicists that are now being used to study solids.

D.10 Theoretical particle physics is one of the most rapidly developing and arguably the most exciting areas of theoretical physics. It has therefore attracted the attention not only of applied mathematicians, but of pure mathematicians, who have further developed the mathematics underlying current particle physics theories. Some of these developments have now found uses in other areas.

D.11 In our discussions with scientists from these related fields we have been impressed by their insistence on the need for continued UK expertise in particle physics at all levels, including courses in the undergraduate curriculum and active British experimental and theoretical work.

THE UTILITY OF HEPP RESEARCH

D.12 Several witnesses have asserted that the very fact that fundamental research is concerned with exploring the limits of our knowledge, means that the results of such research are in principle so unpredictable that any attempt to assess potential utility is wholly futile. It has also been argued that since, in the past, fundamental discoveries in atomic and nuclear physics have led to applications of the greatest importance, it is unreasonable to expect less from recent discoveries in high energy physics.

D.13 It must be common ground that attempts to assess the significance of major discoveries in the past have frequently been dramatically and, with hindsight, ludicrously wrong. In paragraph B.5, however, we have argued that whilst it is indeed impossible to predict the nature and importance of the applications that can flow from a fundamental discovery in science, it is not unreasonable to talk about the probability of utilitarian success. Thus while there may be little to choose in intellectual excitement between charmed quarks, quasars and recombinant DNA, even at the moment of discovery one would rationally predict that the last of these would be more likely (in, say, the next 30 years) to lead to applications than would either of the others.

D.14 Although the atomic and nuclear physics research of the first few decades of this century has had a major impact in other fields, few of the advances made in nuclear or particle physics since then have found major applications. This apparently diminishing return may be a consequence of lengthening timescales between discoveries and practical applications, and has sometimes been attributed in part to the continuing increase in the energy required at the frontier of the subject. One possible application which has recently been re-examined is that of using muons to catalyse fusion, thus producing a cheap and inexhaustible energy supply without the need for high temperature plasmas and the associated containment problems. Should any long-lived or stable heavy charged particles exist, they would also serve to catalyse fusion, as would free quarks. Another possible application, which relies on the behaviour of neutrino interactions discovered in the 1970s, is the use of neutrino beams, derived from accelerators larger than any yet built, to prospect for minerals and for oil; this seems technically feasible, but is not commercially viable using existing technologies. According to current Grand Unified Theories (C.7), proton decay should be catalysed by the predicted magnetic monopoles; this could, in principle, provide a source of energy. As to future discoveries, the recent exciting development of unified theories for forces and particles may eventually have a profound practical impact, but the possibility of this within the next twenty to thirty years appears remote. We believe that the possibility of useful future applications of particle physics research cannot in itself be considered as an important motivation for continuing the research, and that its main justification must rely on its contribution to the advancement of knowledge.

D.15 Many of the letters that we have received in support of UK participation in particle physics have stressed the importance of technological developments derived from the research and its supporting technological infrastructure. However, any major technology-based activity will provide spin-off, and it would be surprising if this were not so for HEPP research. There is a tendency to overestimate the value of such spin-off and, from an examination of the claimed examples, it is clear that few of them are uniquely dependent on particle physics research, although in some cases it may well have accelerated their development. While we accept that spin-off can in general be used as an argument for funding high-technology basic science, we do not consider that it is an important argument specifically in favour of the long-term continued support for particle physics. We consider the particular example of CERN in more detail in Section F.

D.16 More important has been the development of powerful techniques and scientific tools derived from particle physics at various stages in its development or from unique features of accelerators or particle detectors. The following are examples.

i. Radiotherapy using radiation from accelerators, such as electrons and pions; the latter are of particular interest because pions can be aimed at a specified depth within tissue and hence cause less damage to healthy cells surrounding tumours.

ii. Synchrotron radiation; to the high energy physicist this is an undesirable by-product(C.12), but it provides beams of electromagnetic radiation more intense than those obtainable from any other source over a wide range of wavelengths, and these find application in many fields including studies of super-ionic solids and semiconducting surfaces, and time-resolved X-ray diffraction studies of biologically or chemically interesting events. In Europe there are powerful sources of synchrotron radiation, which are used for these applications, at Daresbury, Hamburg and Paris; in addition a small prototype synchrotron radiation source is currently being built in Berlin to test its use for X-ray lithography.

iii. Neutrons from spallation reactions; the bombardment of nuclei with pulses of accelerated protons produces neutron pulses, of controllable energy. These are of use in a wide range of physical and chemical research.

iv. Muon spin rotation; when a muon decays, the direction of the emitted electron reflects the direction of the muon's spin and how it has changed, or rotated, during the muon's lifetime of 2×10^{-6} seconds; this effect only occurs because of violation of "mirror" symmetry, or parity, which was generally considered impossible before it was predicted by particle physicists in 1956. Muon spin rotation can be used to examine physical and chemical interactions in the 10^{-6} to 10^{-9} second time range where the complementary techniques of nuclear magnetic resonance and electron spin resonance are not applicable; it has thus found applications in solid state physics, in chemistry and in biophysics.

v. Positron tomography; positrons annihilate with electrons in ordinary matter, emitting two gamma rays which can be detected with multiwire proportional chambers, allowing the positron's position to be reconstructed. This technique has found application both in medicine and in the study of engine lubrication, using radioactive isotopes that are positron emitters. By firing positrons into metals it is possible to obtain information on their electronic structure and to locate points where fatigue is about to develop, e.g. in turbine blades.

It should be noted that the SERC has funded the construction of both synchrotron radiation and spallation neutron sources and that larger European synchrotron and spallation neutron sources are being actively considered.

E. PARTICLE PHYSICS RESEARCH IN THE UK

THE HEPP COMMUNITY

History

E.1. The origins of experimental particle physics in Britain go back to Sir Joseph Thomson and Lord Rutherford, but it was not until after the 1939-45 war that, as part of nuclear physics, the subject emerged as a coherent academic discipline requiring its own specialized facilities. Initially the research was dominated by studies of cosmic rays, in which UK physicists played a leading role. Later, particle accelerators were built at a few UK universities but they were smaller than those in the United States and could not compete effectively. The UK decision to join CERN (1952-54) and the creation of the National Institute for Research in Nuclear Science (NIRNS) in 1958 formed the basis of the national research effort. During that decade also, "high energy" or "particle" physics began to become distinct from "nuclear" physics ie the study of the behaviour of the nucleus.

E.2. The new subject, the study of which required beams of particles of high energies, was beginning to explore matter at the sub-nuclear level. The synchrotrons and other accelerators in a number of UK universities were not capable of reaching high enough energies to be useful in this respect, and HEPP experimentation was done centrally at CERN or in the two NIRNS laboratories. These two, Daresbury and the Rutherford High Energy Laboratory (later the Rutherford Appleton Laboratory, RAL), were transferred to the Science Research Council (later the Science and Engineering Research Council, SERC) on its creation in 1965.

E.3. Centralization, to allow access to machines of the highest energies available, was taken a further step forward in the 1970's, when the accelerators in the two national laboratories were closed down, and the whole experimental programme was transferred overseas, principally to CERN. The cost of UK research in particle physics decreased significantly in real terms during that decade and into the early 1980s, owing initially to the closure of the national accelerators and later to a reduction in the cost of CERN once the Super Proton

Synchrotron (SPS) was completed. Towards the end of this period there was also a considerable reduction in the funding of experiments due to pressure on SERC funding, and this was accommodated by cutting the support programme, including the manpower of the RAL.

E.4. During the past few years the two national laboratories have both become multi-disciplinary. At the RAL only about 25% of the budget is now used for particle physics. Co-ordination and funding of the research programme is done through the RAL and equipment is built there for university groups to use in experiments at CERN. At Daresbury there is no longer any particle physics activity, but about a third of the Laboratory's budget supports a national facility for the study of what has now come to be known in the UK as "nuclear structure" research, but is usually still referred to in other countries as "nuclear physics".

Present Community

E.5. Table E.I lists the 22 universities or university colleges that have research groups supported by the Particle Physics Committee of the SERC, including small experimental groups involved in the study of low energy neutrons at ILL and in cosmic ray research. This table gives details of the academic staff involved that is funded by the University Grants Committee (UGC) and of the international laboratories used by the experimental groups in 1984. Tables E.II and E.V give further details of the experimental and theoretical groups respectively.

E.6. The UK particle physics community consists of just under 400 post doctoral physicists and 240 post-graduate students, with the following distribution between experimental and theoretical particle physics in 1984:

Physicists	University		RAL Staff		Research Students
	Academic Staff	Post-doctoral Fixed Term	Permanent	Fixed Term	
Experimental	133	80	16	29	104
Theory	90	34	6	6	132
Total	223	114	22	35	236

These figures are roughly in line with those in other large Member States of CERN. In addition about 270 support staff are associated with the experimental groups, of which about 130 are involved with bubble chamber film analysis and are currently being phased out in consequence of earlier cuts in SERC support -a process involving many redundancies.

E.7. To put these figures into context, the 223 university-financed permanent staff involved in HEPP in 1984 represent about 15% of the 1,490 physics staff financed totally by their university, and the 136 SERC-financed HEPP research students account for a similar percentage of the total of 898 SERC research students in physics.

The Contribution of UK Physicists to Particle Physics

E.8. UK physicists have been involved in many of the major advances in experimental particle physics of the past two decades, including for example:

i. neutrino physics, using the Gargamelle and Big European Bubble Chambers which measured the electric charges of quarks and proved that the net number of quarks in a nucleon is three, which discovered the weak neutral current predicted by the electroweak theory (C.3 and C.6), and which provided the first evidence of effects due to quark binding forces, giving early support to Quantum Chromodynamics (C.5);

ii. muon physics, which has been used to probe the structure of nucleons, and includes the work of the European Muon Collaboration on the EMC effect (D.5 and C.20);

iii. the discovery of the gluon (C.3) in the experiments on PETRA at DESY;

iv. the discovery of the $W^{\pm}$ and Z and of the top quark on the SPS $\bar{p}p$ collider.

E.9. The influence of UK physicists at CERN is demonstrated by the number of experiments at the Laboratory that involved British participation, and by the number of experiments with British spokesmen. The figures since 1975 are:

		Experiments with UK Participation		Experiments with UK Spokesmen	
Accelerator	No of Experiments	Number	% of Experiments	Number	% of all Experiments
SPS[1]	119	68	57	30	25
ISR	37	7	19	5	14
PS	63	11	17	8	13
TOTAL	219	86	39	43	20

Fixed target and collider

ng the 10 years since 1975 the UK's share of the cost of CERN has varied een 14.0% and 16.4% (Table F.II).

. British physicists have also been active in the development of new nology, including work on high field magnets and superconducting cables, -automatic measurement of bubble chamber pictures, and detector technology he area of high resolution drift chambers, ring-imaging Cerenkov detectors large-volume drift chambers for particle identification.

The UK has made major contributions to accelerator design and engineering, most important being that of the late Sir John Adams who led the ruction of both the PS and SPS at CERN, but others too have made important ibutions, in particular to the magnets and control system of the SPS. UK cists have also been involved in the design of machines at DESY in Hamburg t the Fermi National Laboratory (Fermilab) in Illinois.

UK particle theoreticians have been involved as leaders in most of the advances of the past two decades, for example:

I. the discovery that the exact symmetries of nature can be hidden (Goldstone's theorem, Higgs-Kibble mechanism) (C.6); the construction and exploration of unified electroweak theories (C.3, C.6), especially the successful Glashow-Salam-Weinberg model; the development of grand-unified and supersymmetric models (C.7, C.14) and exploration of their consequences for laboratory experiments and for cosmology (C.7); studies of quantum gravity and attempts to unify gravity with other forces;

2. pioneering work on the quark model (C.2) and on the quark-parton model of high-energy interactions, for example development of measures of the net number of quarks in the nucleon and of their charges, derivation of the quark-parton model from QCD (C.5) and proposals for tests of QCD, e.g. the prediction that gluon jets should be seen in ee annihilation (C.3), and numerical simulations of QCD.

E.13. We have received evidence from a large number of foreign physicists about the standing of British particle physicists and we are satisfied that the UK is in general making a very significant and in some cases an outstanding contribution. British physicists have played, and are continuing to play, an important role in many areas of the subject and, through their involvement with the UA1 and three LEP experiments, they are expected to continue to do so at least into the next decade.

PARTICLE PHYSICS AND EDUCATION

E.14. We have received evidence of the extent to which particle physics is taught in undergraduate physics courses from the CVCP and from the Particle Physics Committee, which have both carried out special surveys. It would appear that just over half of the universities and university colleges include particle physics either as a core course or as an option in the final year of the undergraduate course. Of these about one third (10) do not have a research group in the subject. In two of these universities particle physics teachers are imported from another institution, and at some others the course is given by cosmic ray physicists.

E.15. An attitude survey of all first year physics undergraduates was conducted at the instigation of the Particle Physics Committee ad hoc group in the autumn of 1984 to obtain some support for the anecdotal evidence that big science attracts students into physics. The findings show that astronomy and related subjects are the greatest influence at that stage, and that particle physics is also an attractive topic (ref 3).

E.16. At the end of an undergraduate course, one measure of the popularity of a subject is the demand for research studentships, and on this basis particle physics is clearly a leading topic in physics with many applicants for each of the available studentships. This is reflected in the fact that over the period 1979 to 1983 the percentage of new particle physics research students with first class degrees varied from 60% to 85%, while the SERC average was about 35%. There would thus appear to be a basis for the contention that particle physics is the topic that captures the interest of the best physics students.

E.17. The interest shown in particle physics by students is a strong argument for research in this field continuing in the UK, since it is obviously desirable for third year courses in any field to be taught by those active in research in that field, but this is clearly not possible in all fields in every university, so it could not be used as an argument in support of the claim that the present number of particle physics groups should be maintained or even increased.

E.18. We have received letters from particle physicists and a few high technology firms reporting that post-graduate research in particle physics is excellent training, giving students experience of modern technology and of working in large international teams while under pressure to maintain fixed and tight schedules. Most students involved with experiments at CERN and DESY spend about one year at the laboratory and this is very useful experience. There are, however, also some disadvantages in being involved with such large teams and with experiments with long timescales, although we have been impressed by the imaginative way that supervisors have organized students' work so that these are minimized. While some postgraduate work in particle physics is evidently valuable for careers in other areas, the training is clearly very expensive.

E.19. A number of witnesses have indicated their concern that particle physics was taking up too high a proportion of the highest quality students in physics, bearing in mind that each year only one or at most two permanent university positions in that field become available. However, in 1983 there were no more than 33 new graduate students in particle physics with first class degrees, which was only 10% of the total number of physics graduates with this class of degree, a proportion which in our opinion is unlikely to cause an imbalance in UK physics.

EXPERIMENTAL HEPP

The Nature of HEPP Experiments

E.20. One of the main characteristics of research in experimental particle physics is that it is carried out in increasingly large collaborations involving groups from a number of countries; for example the ALEPH detector on LEP involves 6 UK university institutions and 18 other institutions from 7 countries.

E.21. The establishment of a collaboration is, initially at least, a rather informal affair, but all the partners are expected to contribute to the overall effort and to the cost of the experiment. To obtain funds for a proposed contribution to a major experiment, each collaborating group has to satisfy its own national funding body (in the UK the Particle Physics Committee's Particle Physics Experiments Selection Panel) that its proposal should be supported. The collaboration as a whole has to satisfy the relevant laboratory's experiment selection committee that the proposed experiment deserves to be included in the programme for the particular accelerator. In practice the approaches to national funding bodies and to the experiment selection committee are coordinated so that any necessary modifications of the proposal can be made. When the experiment is approved and funding has been obtained by the collaborators, the arrangements are formalized so that each group knows the extent of its commitment.

E.22. To a large extent the influence that a physicist has over the direction and progress of a collaboration depends on what material and intellectual contribution he is able to make, for example in the provision of components of the detector and its associated equipment, of software for data collection, and of computing power for data reduction and analysis; and finally on his expertise in interpreting the results. The materials cost of modern detectors for colliders may be as much as £25-£40M and the total cost including manpower considerably more than this. Each group is responsible for designing and constructing part of the apparatus, which is subsequently transported to the accelerator. In the case of three of the LEP experiments there is also a contribution to a fund to finance items that are the joint responsibility of the collaboration. The total cost of the UK's contribution to the three LEP experiments up to 1990 will be about £35M, including the cost of materials and of the collaborations' common funds (about £9M), of support staff at RAL, and of travel and subsistence by university staff. The more important contributions to the LEP detectors being offered by UK institutions are outlined in Appendix 7. A breakdown of each country's contribution to the materials cost of the LEP experiments (in M Swiss francs) is given in Table F.I in the next section.

E.23. Each collaboration has a spokesman who represents its interests to the Laboratory, and who convenes meetings to discuss progress or to consider the experimental results. The raw information from an experiment is available to all participants, but usually an agreement is made for an equitable sharing of at least the initial analysis of the results. Thereafter institutions may specialize in particular areas of interest. Papers based on data from the experiment are published under the names of all the collaborators. As an example, Appendix 8 gives a brief outline of the UK's contribution to the analysis of data from the UA1 experiment.

E.24. Details of the staff involved in experimental HEPP in 1984 are given in Table E.II. It will be seen that there are nine large groups, which together account for 80% of the physicists and 95% of the university-based support staff:

	Physicists*	Technical Support Staff			
		Graduate1	Technician2	Bubble3 Chamber	Total
Oxford	27	13	19	38.5	70.5
Imperial College	25	8	11	24	43
Birmingham	24	5	8	25.5	38.5
Liverpool	22	2	9	8.5	19
University College	18	5.75	10	13	28.75
Glasgow	17	3	7	8	18
Manchester	15	5	9.75	-	14.
QMC	12	1	8	1	10
Cambridge	11	2	4	9.5	15.5

1. Graduate engineers and programmers
2. Technicians and operating staff, excluding those included in 3.
3. Staff associated with bubble chamber analysis, which is currently being phased out.

Bristol and Lancaster have 10 and 8 physicists respectively, but few support staff, and the remaining groups each have six physicists or less. The smaller groups almost invariably collaborate with one or more of the larger UK groups, while still providing their own distinctive contribution to the work.

E.25. There are two reasons for the large numbers of support staff associated with particle physics research. In the first place, bubble chamber work requires the digitization of large numbers of photographic images and, although some ingenious aids have been developed, this is still a labour-intensive process. However, bubble chamber work is now being phased out in the UK. SERC funding of it will cease completely by the end of 1987, with the consequential reduction of about 90 SERC supported and 40 university supported film scanning staff. The other activities requiring substantial numbers of professional and technical support staff are the processing and analysis of large quantities of data and the design, development, construction and operation of major components of the detectors. The size and complexity of work in these areas now demands increasing effort and redeployment of a few film scanning posts into these areas is occurring. Only the larger groups listed above undertake extensive development and construction work; the smaller groups make use of facilities at other universities or at RAL. The number of support staff per physicist in the UK is substantially below that in France, FRG and Italy.

Facilities Used by the Community

E.26. A summary of the the experiments associated with each university group, in preparation or actually running during 1984, is included in Table E.I and further details of the main areas of experimental work are given in Table E.III and Appendix 9. Most of the current experiments are connected either with the $p\bar{p}$ collider or with fixed-target facilities on the SPS at CERN, although significant research is also being carried out on the PETRA collider at DESY and at Fermilab. There are also a few non-accelerator experiments, engaged in the search for proton decay, for fractional charge and for magnetic monopoles.

E.27. The main basis of the community's future experimental work is the large electron-positron (LEP) collider; about 50% of academic UK physicists are associated with preparations for three of its four detectors. Some members of the community will continue to be associated with the SPS $p\bar{p}$ collider and with fixed target experiments, but the number of the latter will decline. At DESY all UK involvement with the PETRA collider will cease after 1986, and the physicists involved with completed or prematurely terminated experiments hope to continue their research on new facilities. About 25% of the total community wish to be associated with experiments on the new ep collider (HERA) and are actively involved with proposals in connection with two prospective collaborations.

E.28. The community has stressed to us the need for the UK to be involved with some experiments outside CERN, in order to cover a wider range of the important areas of particle physics than can be provided by a single laboratory, even one the size of CERN. In particular they have stressed the advantages of participation in experiments on the HERA ep collider to complement those on the $p\bar{p}$ and $e\bar{e}$ colliders at CERN. (C.15). In view of the probable continuing limitations on the available resources, however, it will be necessary to weigh the relative advantages of making maximum use of the facilities at CERN against the benefits of spending some of the funds on experiments elsewhere.

E.29. Although all accelerator-based high energy particle physics research is carried out at overseas laboratories, much of the supporting work by British groups is undertaken at home. For example, many groups are involved with basic detector development and some important advances in this area have originated in the UK. As mentioned above, UK groups contribute major components of the detectors at overseas laboratories; sub-components are usually produced by industry, but the final assembly and testing is almost always carried out in university workshops or at RAL and this often involves a considerable amount of effort.

E.30 After the data have been obtained, their detailed analysis is mainly carried out at the home institutions of the collaborating groups. In the case of the UK, this work is aided by the fast data links between RAL, DESY and CERN, and also by the well-developed networking facilities within the UK. The British share of the processing is carried out on computers at RAL and the departmental computers of the larger groups.

The Organization of Support for Experimental Particle Physics

E.31. The SERC's funding of domestic expenditure on experimental particle physics, apart from studentships and fellowships, is provided via the Particle Physics Committee (PPC) through two channels:

i. grants for the support of staff and equipment at universities are made on a rolling programme allocated each year by the PPC on the basis of recommendations by its Experimental Grants Sub-Committee and expenditure in 1983/84 totalled £3.14M:

ii. the direct cost of experiments, including the cost of manpower support from RAL and travel, is allocated by the PCC on the basis of recommendations by the Particle Physics Experiments Selection Panel and amounted to £12.05M in 1983/84 distributed between the following functional heads:

experimental equipment and running costs	£3.29M
travel (RAL and university staff)	£2.26M
RAL manpower directly allocated to experiments	£3.89M
RAL overheads	£2.61M
TOTAL	£12.05M

The nominal allocation of computing facilities at RAL to experimental HEPP in that year was about £3M but the method of allocating central computing facilities to the various SERC Boards is at present being reorganized.

E.32. An alternative way of considering the direct cost of experiments is to associate the equipment and manpower costs with major experiments or groups of experiments. Table E.IV (II) gives such an analysis in terms of expenditure and RAL manpower associated with experiments on the LEP, SPS, ISR and LEAR facilities at CERN, DESY and other sites and also into new techniques.

Role of the Rutherford Appleton Laboratory

E.33 At present just under 25% of the resources of RAL are allocated to the particle physics community, a major change from the situation in the mid-1970s when all the resources of what was then the Rutherford Laboratory and much of those at the Atlas Laboratory Computing Centre were used to support the Nuclear Physics Board. Fig E.1 shows the change in staff associated with specific Boards since 1970.

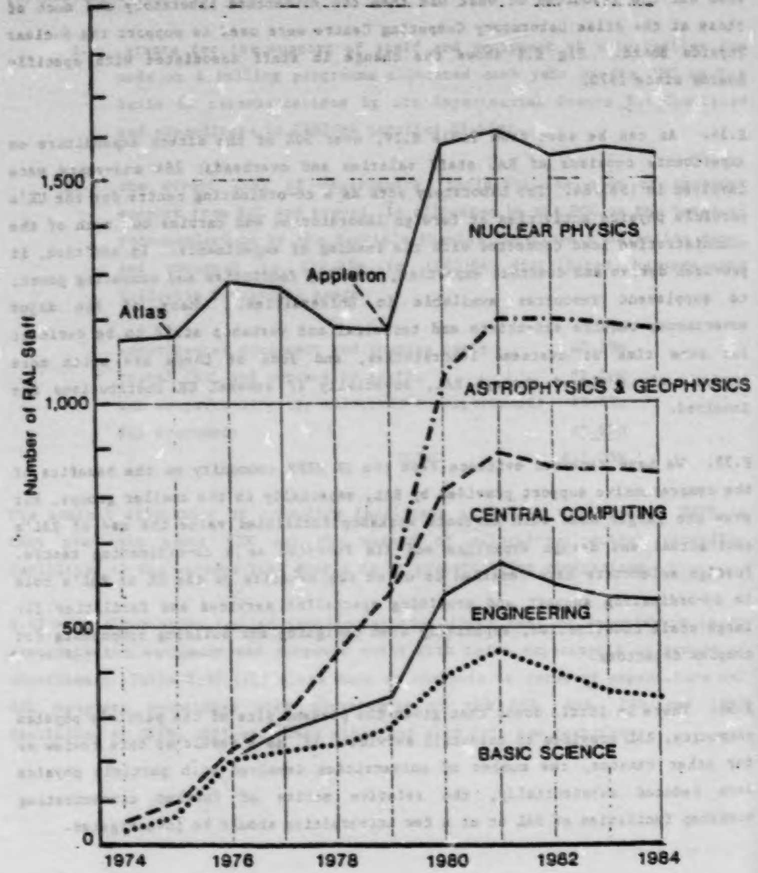
E.34. As can be seen from Table E.IV, over 50% of the direct expenditure on experiments consists of RAL staff salaries and overheads; 284 man-years were involved in 1983/84. The Laboratory acts as a co-ordinating centre for the UK's particle physics activities at foreign laboratories and carries out much of the administrative load connected with the funding of experiments. In addition, it provides design and contract expertise, workshop facilities and computing power, to supplement resources available in universities. Many of the major experiments require scientists and technical and workshop staff to be resident for some time at overseas laboratories, and some of these are often more conveniently employed through RAL, especially if several UK institutions are involved.

E.35. We have received evidence from the UK HEPP community on the benefits of the comprehensive support provided by RAL, especially to the smaller groups, but even the larger ones with adequate workshop facilities value the use of RAL's contractual and design expertise and its function as a co-ordinating centre. Foreign scientists have remarked to us on the benefits to the UK of RAL's role in co-ordinating support and providing specialist services and facilities for large scale construction, especially when designing and building components for complex detectors.

E.36. There is little doubt that given the present size of the particle physics community, RAL provides an essential service. If, as a result of this review or for other reasons, the number of universities involved with particle physics were reduced substantially, the relative merits of further concentrating workshop facilities at RAL or at a few universities should be investigated.

FIG. E.1

DISTRIBUTION OF RAL STAFF TO SERC BOARDS 1974/1984



THE THEORETICAL PARTICLE PHYSICS COMMUNITY

E.37. Table E.V gives details of the theoretical particle physics community, which is spread over 20 universities and university colleges. The total number of permanent academic physicists and applied mathematicians involved is 74 and in 1983/84 the SERC expenditure on grants totalled £0.34M. A further £0.35M was provided through RAL for theoretical support, mainly the cost of the RAL Theory Group, plus about £0.14M for computing facilities at the Laboratory.

E.38. The degree of involvement of theoretical particle physicists with experiments varies from an extremely close relationship to an almost complete independence from current experimental research. Those physicists who are concerned with phenomenological problems have stressed the need for very close contact with experimentalists, and the impossibility of relying on published data if they are to remain at the forefront of the subject. They have also explained that, because of the extended periods over which experiments are designed and built they have to keep in touch with a relatively large number of experimental groups. Such theoreticians would be severely handicapped by a UK withdrawal from experimental particle physics and they feel that their work would eventually be reduced to an ineffective level, even if increased grants were made available for travel. Although the more mathematically oriented physicists agree that in the short term withdrawal from experimental work would have much less effect on them, these too were concerned that in the long term their effectiveness would be reduced.

E.39. Both groups of theoreticians make use of the CERN Theory Division, which is considered further in the next section. They were all concerned about the effect on physics teaching if the UK were to withdraw from experimental work. The senior members of the theoretical community stressed that, although they personally would still be able to continue with their research at some level after such a withdrawal, it was their more junior colleagues who would be most affected, and they also doubted whether it would be possible to attract such able students in the future.

E.40. It is our view that withdrawal from experimental particle physics would reduce considerably the effectiveness of the UK's phenomenologically oriented theoretical work. No doubt some theoreticians would continue to make useful contributions if there were an increase in finance for sabbatical visits to centres of excellence throughout the world, but the close interdependence of theoretical and experimental work makes it unlikely that the UK could rely entirely on theoretical particle physicists to maintain the UK's expertise in the subject as a whole.

THE OVERALL COST OF PARTICLE PHYSICS

E.41. The overall cost to the SERC of particle physics research in 1983/84 can be summarized as follows:

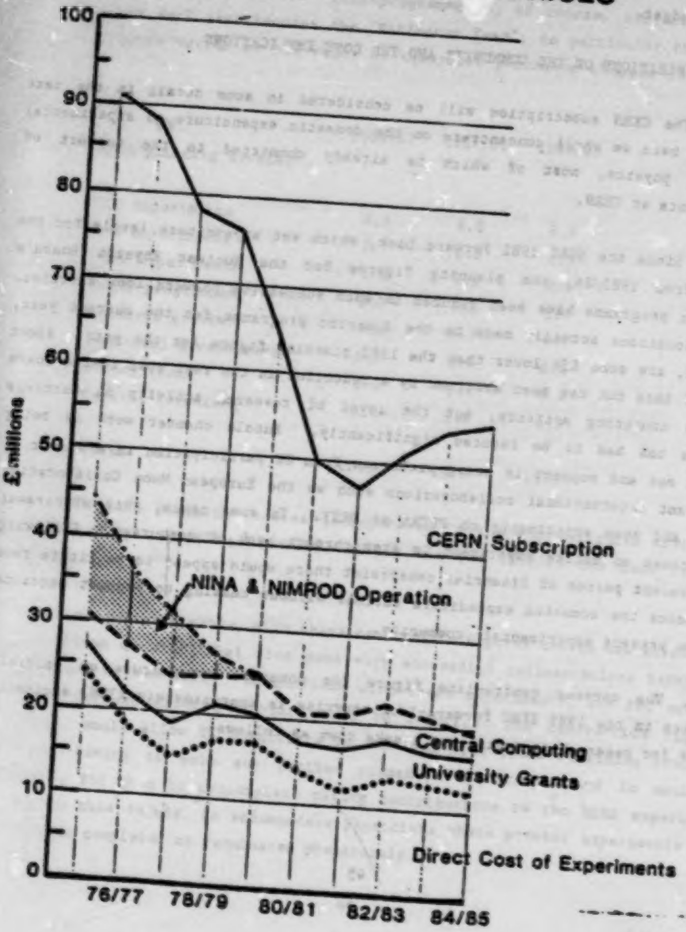
Grants to experimental groups	£3.1M
Grants to theoretical groups	£0.4M
Cost of experiments (including travel)	£12.1M
Computing (capital and recurrent Costs)	£3.5M
Studentships	£0.8M
SERC HQ overheads	£0.1M
CERN Subscription	£32.1M
Total	£52.1M

The total was 19.7% of the SERC expenditure and 10.1% of the DES Science budget of £517M. In addition the universities contribute about £5M each year in the form of academic and support staff salaries, small scale laboratory equipment etc.

E.42. Fig E.2 illustrates the changes during the last ten years in the major components of the total SERC support costs for HEPP. The detailed figures are given in Table E.VI, and from this it can be seen that there has been a significant drop in the domestic expenditure since 1975/76, from about £44M to £20M at 1984 prices, of which about £13m was the result of closure of the UK accelerators (NINA and NIMROD). There has also been a fall in the real cost of

FIG. E.2

SERC EXPENDITURE ON PARTICLE PHYSICS 1975/76 to 1984 AT 1984 PRICES



the CERN subscription, although the increase in the UK's GNP relative to other Member States, and the fall in the value of the pound relative to the Swiss franc, have resulted in an increase of £8M since 1981, again at 1984 prices. The Treasury provided some compensation for the increased share of the CERN budget after 1983, hence only part of the £8M has come from other areas of the Science budget.

FUTURE ASPIRATIONS OF THE COMMUNITY AND THE COST IMPLICATIONS

E.43. The CERN subscription will be considered in some detail in the next section; here we shall concentrate on the domestic expenditure on experimental particle physics, most of which is already committed to the support of experiments at CERN.

E.44. Since the SERC 1982 Forward Look, which set expenditure levels for the years from 1983/84, the planning figures for the Nuclear Physics Board's domestic programme have been reduced in each successive forward look exercise. The allocations actually made to the domestic programme for the current year, 1985/86, are some £5M lower than the 1982 planning figure for the year. About half of this cut has been absorbed by a reduction in the real cost to the Board of its computing activity, but the level of research activity in particle physics has had to be reduced significantly. Bubble chamber work is being phased out and support is being withdrawn from UK participation in a number of important international collaborations such as the European Muon Collaboration (EMC) and some experiments on PETRA at DESY. In some cases, this withdrawal will cause an entire experiment to stop through lack of resources. Following this recent period of financial constraint there would appear to be little room to reduce the domestic expenditure further without ceasing to support sections of the present experimental community.

E.45. The current centre-line figure for domestic expenditure on particle physics in the 1985 SERC forward-look exercise is approximately £20M, excluding funds for research students, and breaks down as follows:

Cost of experiments funded through RAL	£13.1M
University Grants	£4.8M
Central Computing	£2.6M

The proposed distribution of funds during the first three years of the forward-look period is shown below. This programme is, of course, subject to annual revision as each year becomes the "Estimates Year"; in particular the research grants figure varies as the value of equipment purchases changes from year to year.

£M (at cash-planning levels)[1]	1986/87	1987/88	1988/89
LEP experiments	6.4	6.8	6.9
SPS experiments	2.7	1.8	1.3
DESY experiments	1.2	2.0	2.9
Other programmes	2.0	1.8	1.0
Research grants	4.8	4.7	4.7
Technical development	0.4	0.4	0.4
Theory (RAL)	0.4	0.4	0.4
Central computing	2.4	2.0	1.9
Total	20.3	19.9	19.5

1. The cash planning indices incorporated in the above figures are: from 1985/86, +3%; 1986/87 to 1987/88, +2.5%; and for 1988/89 the same level as 1987/88.

2.46. As indicated above, with these centre-line figures notice has already had to be given of withdrawal from some very successful collaborations before the completion of the work. To continue with these experiments, the PPC estimate that a further £1.4M per year would be required. The centre-line figures, however, would allow UK physicists to continue with their remaining programme without having to make any further premature withdrawals and it would be possible for them to contemplate making contributions to two HERA experiments ater in this decade, to accommodate physicists whose present experiments will ave been completed or terminated prematurely.

E.47. We have examined the effect of various levels of reduction on this baseline programme. A major constraint, however, is the UK's commitment to the three LEP experiments, costing in total over £6M per year in direct costs through RAL up to 1989/90. To withdraw from any of these experiments at this stage would cause severe funding problems to the collaboration and, at the very least, major delays in implementing the experiment. When the detectors are in operation, the UK groups will be responsible for the maintenance of their equipment: in addition there will be travel and other costs associated with running the experiment and the analysis of the data, but we would expect a substantial reduction in the costs associated with these experiments after 1990, although some upgrading of the detectors would be probably be desirable, especially when the energy of LEP is increased.

E.48. It should be noted that reductions in the domestic expenditure, which at present accounts for about 38% of the total expenditure on particle physics, would reduce the total expenditure by a relatively small percentage. Also, cuts in domestic expenditure would reduce the value obtained from membership of CERN.

E.49. It is estimated by the Particle Physics Committee that a 40% cut in the domestic programme before 1989/90 would only allow the funding of the UA1 and the three LEP experiments, and that this would leave about 50% of the academic physicists unfunded. Furthermore, the selection of those continuing to be funded would be determined primarily by historical accident. A 30% cut on a similar timescale would allow the remaining existing commitments to continue to the natural end of the experiment, but would not allow for new work for those members of the community whose experiments are now being phased out; it is estimated that about 30-35% of the community would be unfunded. As with the 40% cut, it is doubtful if the UK community could continue to play an active role in future developments apart from the UA1 and the three LEP experiments. A 20% cut by 1989/90 would still leave perhaps 20% of the community unfunded, but would provide some flexibility for a more orderly reduction in the size of the community and enable about 40% of the proposed work on HERA to be carried out.

E.50. In 1990 and beyond, the expenditure on the three LEP experiments should fall and this could provide scope for further reductions, or for participation in new experiments. If it were proposed to upgrade the LEP experiments, the UK would have the opportunity to consider whether it should continue to be involved with all three.

TABLE E.1

THE UK UNIVERSITY PARTICLE PHYSICS COMMUNITY IN 1984

	UGC Funded Physicists		Use of Experimental Facilities[1]					
			CERN				DESY	Other
	Theory	Experiment	LEP	$p\bar{p}$	FT	Other		
Birmingham	5	17	OPAL	UA1	1	LEAR	-	FNAL
Bristol	3	5		-	1			
Cambridge	10	5	OPAL	UA5	-	ISR		
Durham	10.5	0						
Edinburgh	6.5	3	ALEPH	-	1			
Glasgow	5	11	ALEPH	-	1		CELLO	
Kent	4	0						
Lancaster	2	6	ALEPH	-	2		JADE	
Leeds		1						Cosmic Ray
Liverpool	3	13	DELPHI	-	2			
London[2]								
Imperial	12	16	ALEPH	UA1	1		TASSO	MP,FC,FNAL
King's College	2	0						
QMC	6	10	OPAL	UA1		(LEAR (ISR		LA,SNS
Bedford/RHC/ Westfield	5	5	ALEPH	-		LEAR		LA
UCL/Birkbeck	3	15	OPAL	-	2			PD
Manchester	3	9	OPAL	-	1		JADE	
Open	(3)							
Oxford	7	23	DELPHI	-	2	ISR	TASSO	SNS, PD, FNAL
Sheffield	0	2	ALEPH	-	2			
Southampton	4	3	ALEPH	-	1			
Surrey		1				LEAR		LA
Sussex	3	2						ILL

pp	SPS proton anti-proton collider
FT	SPS fixed target
LEAR	Low Energy Antiproton Ring
ISR	Intersecting Storage Rings (Closed June 1984)
FNAL	Fermi National Accelerator Laboratory
MP	Search for monopoles
FC	Search for fractional charge
LA	Los Alamos Meson Production Facility
SNS	Spallation Neutron Source
PD	Proton decay experiments

1. Extracted from Particle Physics Experiments 1984: Rutherford Appleton Laboratory (RL-85-001)

2. Minor changes in some of the numbers shown will result from the 1984 London college mergers

TABLE E.II
EXPERIMENTAL PARTICLE PHYSICS GROUPS AT OCTOBER 1984

University	UGC Funded Physicists[1]	SERC Funded Physicists[2]	Support Staff[3]		Total		Students	
					UGC	SERC	SERC	Other
Birmingham	17	6	38.5	(25.5)	32.5	30	8	0
Bristol	5	3	2		6	4	2	1
Cambridge	5	6	15.5	(9.5)	10	16.5	5	1
Edinburgh	3	1	1		3	2	1	0
Glasgow	11	6	18	(8)	19	16	5	1
Lancaster	6	4	2		6	6	5	0
Leeds[4]	1	1	2		2	2	1	1
Liverpool	13	9	19.5	(8.5)	20	21.5	7	2
London								
Imperial	16	9	43	(24)	31	37	11	5
QMC	10	2	10	(1)	15	7	4	1
Bedford/RHC/ Westfield	5	3	5		9	4	1	2
UCL	15	3	28.75	(13)	28.75	18	6	1
Manchester	9	6	14.75		15.75	14	8	1
Oxford	23	4	70	(38.5)	61	36.5	13	2
Sheffield	2	3	2.5		4.5	3	3	1
Southampton	3	1			3	1	0	3
Surrey	1	1			1	1	1	0
Sussex	2	1	2		3	2	0	1
(Durham[5]	0	0	2		0	0	0	0)
Total	147	69	276.5	(128)	270.5	221.5	81	23
RAL		45[6]	77.5	(7.5)		122.5		
Total	147	114	354		270.5	344.5	81	23

1. Includes a few UGC funded post-doctoral fellows
2. Includes SERC Advanced and Senior Fellows
3. Includes programmers, engineers, technicians, operating staff and bubble chamber film scanners funded by both the UGC and SERC (figures in parenthesis are the staff numbers included in the totals which are associated with bubble chamber work).
4. Cosmic Ray
5. Experimental Data Base Work
6. 16 permanent and 29 fixed term physicists

TABLE E.III

SUMMARY OF PARTICLE PHYSICS EXPERIMENTS COLLECTING DATA OR IN PREPARATION IN 1984, THAT INVOLVE THE UK COMMUNITY

CERN

LEP: ALEPH (Edinburgh, Glasgow, Lancaster, Imperial, RHC, RAL, Sheffield Southampton)
DELPHI (Liverpool, Oxford, RAL)
OPAL (Birmingham, Cambridge, Birkbeck, QMC, UCL, Manchester)

SPS $p\bar{p}$ collider: UA1 (Birmingham, Imperial, QMC, RAL)
UA5 (Cambridge)

SPS Fixed Target: High Energy Muon Physics (Lancaster, Liverpool, Oxford, RAL, Sheffield)
Hadron Beam Experiments (Birkbeck, Bristol, Glasgow, Liverpool, UCL, RAL)
High Energy Photon Physics (Imperial, Lancaster, Liverpool Manchester, RAL, Sheffield, Southampton)

LEAR (Bedford, Birmingham, QMC, RAL, Surrey)

ISR (Closed June 1984) (Cambridge, QMC, Oxford, RAL)

DESY

PETRA: CELLO (Glasgow)
JADE (Lancaster, Manchester, RAL)
TASSO (Imperial, Oxford, RAL)

ILL, Grenoble (Sussex, RAL)
SNS, RAL (Oxford, RAL)
FERMILAB, (Neutrino physics) (Birmingham, Imperial, Oxford, RAL)
SLAC (RAL)

NON-ACCELERATOR EXPERIMENTS

Search for Magnetic Monopoles	(Imperial)
Search for Fractional Charge	(Imperial, RAL)
Proton Decay	(UCL, Oxford, RAL)
Solar Neutrinos	(Oxford)

TABLE E.IV
DOMESTIC EXPENDITURE ON HEPP IN 1983/84

	Direct Effort Man years	Requisitions £M	Total Costs £M	£M
I. GRANTS TO UNIVERSITIES		£M		£M
Staff		2.39		
Recurrent costs		0.60		
Equipment		0.51		
Total Grants		3.50		3.50
II. DIRECT COST OF EXPERIMENTS THROUGH RAL				
CERN Experiments				
LEP	64 (23%)	1.35 (23%)	2.81 (23%)	
SPS Collider	13 (4.5%)	0.33 (5.6%)	0.63 (5%)	
SPS Fixed target	102 (36%)	2.44 (42%)	4.78 (39%)	
LEAR, ISR	15 (5%)	0.23 (4%)	0.60 (5%)	
Total CERN	194 (68%)	4.37 (75)	8.81 (71%)	
DESY	23 (8%)	0.60 (10%)	1.13 (9%)	
Other Experiments	44 (15%)	0.66 (11%)	1.67 (14%)	
New Techniques	10 (3.5%)	0.11 (2%)	0.34 (3%)	
Theory	13 (4.5%)	0.05 (1%)	0.35 (3%)	
TOTAL	284	5.79	12.30	
Less Receipts			0.25	12.05
III. COMPUTING				
IV. RESEARCH STUDENTS				2.50
V. SERC HEAD OFFICE OVERHEADS				.08
TOTAL DOMESTIC EXPENDITURE				.10
				19.95

TABLE E.V

PARTICLE PHYSICS: THEORETICAL PHYSICS MANPOWER IN POST AT MAY 1984

	Permanent and Fixed Term Physicists			Research Students	
	UGC		SERC	SERC	Other
	Permanent	Fixed Term			
Birmingham	5		1	2	0
Bristol	3		0	1	0
Cambridge	8	2	3	7	3
Durham	10.5		2	3	3
Edinburgh	6	0.5	2	5	5
Glasgow	5		2	4	3
Kent	4		0	0	3
Lancaster	2		1	0	2
Liverpool	3	1	2	3	2
London					
ICST	8	4	2	7	16
King's	2		0	0	8
QMC	6		1	3	4
RHC/Westfield	5		0	0	0
UCL	3		1	3	2
Manchester	3		2	4	5
Open	3		0	0	2
Oxford	5	2	2	5	11
Southampton	4		2	7	4
Sussex	3		1	2	4
TOTAL	8.5	9.5	24	56	77
RAL			12[1]		

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[1] 6 permanent and 6 fixed term physicists

TABLE E.VI

THE MAJOR COMPONENTS OF HEPP SUPPORT COSTS (EXCLUDING STUDENTSHIPS AND OVERHEADS) AT CURRENT AND CONSTANT 1984 PRICES

Financial years	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984
CURRENT PRICES										
University Grants	1.2	1.6	1.7	2.1	2.1	2.3	4.[illegible]	4.2	3.5	4.2
Experiment costs[1]	9.1	8.4	8.2	9.5	10.9	10.6	10.2	11.3	12.0	12.2
NIMROD/NINA	5.1	3.9	3.5	1.2	0.3	-	-	-	-	-
Central Computing	1.5	2.3	3.0	2.0	2.8	2.5	3.0	3.6	3.5	3.3
CERN	18.6	23.2	23.8	27.7	25.2	22.4	22.5	26.6	32.1	35.5
TOTAL	35.5	39.4	40.2	42.5	41.3	37.8	39.7	45.7	51.3	55.2
TOTAL[2]	30.4	35.5	36.7	41.3	41.0	37.8	39.7	45.7	51.3	55.2
1984 PRICES										
Grants	3	4	3	4	3	3	5	5	4	4.2
Experimental[1]	23	19	16	17	17	14	12	13	13	12.2
NIMROD/NINA	13	9	7	2	1	-	-	-	-	-
Central Computing	4	5	6	4	4	3	4	4	4	3.3
Total Domestic	43	37	32	27	25	20	21	22	21	19.6
CERN	47	52	46	50	39	30	27	30	34	35.5
TOTAL	90	88	78	76	63	50	47	51	54	55.2
TOTAL[2]	77	79	71	74	63	50	47	51	54	55.2
Inflation Factor	2.53	2.23	1.93	1.79	1.53	1.32	1.19	1.11	1.05	1.00

1. Includes cost of RAL Theory Group and the development of new techniques
2. Excluding operating and development costs for NINA and NIMROD (closed in 1976 and 1978 respectively)

F CERN

INTRODUCTION

F.1. In 1951 UNESCO sponsored a meeting of European states interested in considering the practicability of a joint European nuclear laboratory to provide facilities comparable with those becoming available in the United States. At a second meeting in February 1952, 11 nations signed an agreement which established an interim body known as the 'Conseil Européen pour la Recherche Nucléaire' (CERN). In 1954 the interim body was dissolved and the permanent organization was created, and by early 1955 the following 12 states had ratified the Convention which established the European Organization for Nuclear Research: Belgium, France, Germany (FRG), Greece, Italy, The Netherlands, Norway, Sweden, Switzerland, The United Kingdom and Yugoslavia. Subsequently Austria and Spain joined the Organization, in 1959 and 1961 respectively, but in 1961 Yugoslavia withdrew for financial reasons as did Spain in 1968, although the latter rejoined in 1983.

F.2. The site chosen for the Laboratory was Geneva and the first two accelerators were specified in the Convention as a synchrocyclotron (SC) capable of accelerating protons to 0.6 GeV and a proton synchrotron (PS) for energies above 10 GeV. The SC produced its first beam in 1957 and is still in operation for the use of non-particle physicists. The first beam was achieved in the PS in 1959; since then it has been operated at energies up to 28 GeV and has been used as part of the injection system of all subsequent larger accelerators at the Laboratory.

F.3 The next major accelerator was the Intersecting Storage Rings (ISR) with a diameter of 300m, which necessitated the expansion of the Laboratory across the border into France. The ISR was the first proton-proton collider to be built; it came into operation in 1971. It was closed in June 1984 to release manpower and funds for the LEP development.

F.4. In 1971 it was agreed to build a 300 GeV proton synchrotron (SPS) with a diameter of 2.2km, and this reached its improved design energy of 400 GeV in 1976. Subsequently the synchrotron was modified to allow it to be used as a proton-antiproton collider and the first such collisions were achieved in 1981. Since that time evidence has been obtained for the production and decay of W and Z intermediate vector bosons, and probably for the top quark.

F.5. In 1981 all Member States voted in favour of the construction of a large electron-positron colliding beam machine (LEP) optimized to achieve 100 GeV per beam, with a circumference of about 27 km and an initial energy of just over 50 GeV per beam. The first four experiments are expected to start in 1989.

F.6. The CERN Convention has provision for Member States to withdraw after a minimum of one year from the 1st of January following receipt of written notice to that effect by the CERN Council. Nevertheless, as with any high technology enterprise of this nature, the organization has to commit itself for a much longer timescale than this and hence there is a certain moral obligation on Member States not to withdraw in such a way as to to cause major disruption to the scientific programme.

F.7. In recognition of the commitment to the construction of LEP, and to contracts that in some cases would not be complete until 1969, it was suggested during consideration of the LEP project by the CERN Council that, for the LEP construction period, Member States should enter into a gentlemen's agreement not to withdraw. This was accepted in principle by the Member States, but the UK delegate gave warning that Britain might have to consider withdrawing from the LEP project, and hence from CERN, if:

(a) the LEP project turned out to be much more costly than had been planned and it was not possible to build it within a reasonable timescale;

(b) the budget of the SERC fell in real terms over a period of time.

F.8. In addition to its obligation to the construction of LEP, the UK is also committed to constructing major components for 3 of its four detectors. The total cost to the SERC of UK involvement in the LEP experiments, including staff costs and RAL overheads, will be about £35M up to the start of LEP, of which about a quarter has already been paid or committed in terms of contracts.

CURRENT FACILITIES AT CERN

F.9. The main present facilities at CERN, and the number of physicists associated with each in 1984, are:

Synchrocyclotron (SC) - (130)
Low Energy Antiproton ring (LEAR); (250)
Super Proton Synchrotron (SPS) - fixed target experiments (1100)
- proton anti-proton collider (250)

F.10. The Synchrocyclotron is now used as a source of muons for muon spin rotation studies, and produces radioactive isotopes of about 40 elements for the ISOLDE programme. The Low Energy Antiproton Ring has also attracted atomic and nuclear structure physicists and is a unique intense source of low-energy antiprotons of well-defined energy.

F.11. The SPS in its original fixed target mode provides a range of secondary beams, as well as protons accelerated up to 450 GeV. The main areas of interest to the UK community are: high energy muon physics, neutrino physics, hadron beam experiments, and high energy photon physics. Further details of these are given in Appendix 9. The SPS is also used for about half the year as a $p\bar{p}$ collider with a maximum centre-of-mass energy of 640 GeV. The antiproton intensity is being enhanced through the development of a new antiproton collector, ACOL, which will increase the interaction rate of the collider by at least a factor of 10. This enhancement will be available in 1987 and will prolong the useful life of the collider to the end of the decade at least. ACOL is being partly funded by a loan from all Member States except the UK, and the repayment of this loan is a prior charge on the budget for 1989 and 1990. The centre-of-mass energy of the collider can now be increased to 900 GeV by using it in a special mode (C.14).

F.12. The great majority of users of the facilities at CERN are physicists from institutions within Member States who visit the Laboratory while their experiments are being prepared and run. In addition about 130 CERN fellows and 170 paid associates are working at the Laboratory at any given time. The total number of users, including paid and unpaid associates, some of the outside technicians, students and fellows, has more than doubled since 1977 from about 1600 to over 3300 in December 1983 (Fig F1). The latter figure includes about 500 from non-member states (about 15%).

F.13. Before the LEP project, about 50% of the cost of experiments was borne by the CERN budget and about 50% by the collaborating institutions, but as much as about 85% of the cost of the four LEP experiments is being paid by the latter. An analysis of the approximate contribution to the materials cost of LEP experiments, as estimated in 1983, is given in table F.I in millions of Swiss francs (MSF). Figures for the total cost to each country are difficult to obtain, but in the case of the UK the staff costs, RAL overheads and travel costs are likely to be at least twice as large as the materials costs, and the situation is probably the same in other countries.

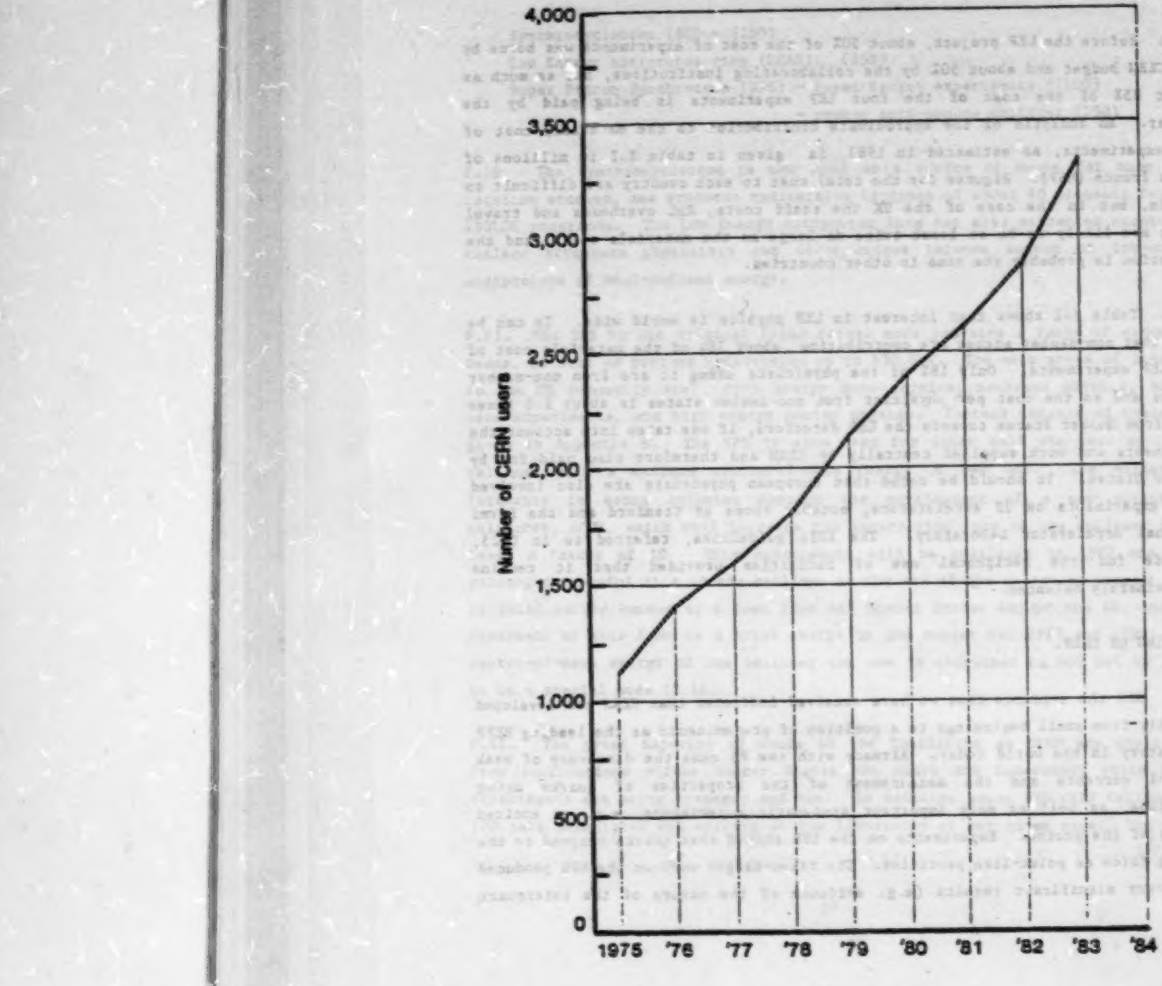
F.14. Table F.I shows that interest in LEP physics is world wide. It can be seen that non-member states are contributing about 38% of the materials cost of the LEP experiments. Only 18% of the physicists using it are from non-member states and so the cost per physicist from non-member states is about 2.8 times that from Member States towards the LEP detectors, if one takes into account the components and work supplied centrally by CERN and therefore also paid for by Member States. It should be noted that European physicists are also involved with experiments on US accelerators, notably those at Stanford and the Fermi National Accelerator Laboratory. The ICFA guidelines, referred to in C.25, provide for the reciprocal use of facilities provided that it remains approximately balanced.

STANDING OF CERN.

F.15 All the evidence that we have received indicates that CERN has developed steadily from small beginnings to a position of pre-eminence as the leading HEPP laboratory in the world today. Already with the PS came the discovery of weak neutral currents and the measurement of the properties of quarks using neutrinos, as well as many important systematic experiments, e.g. on excited states of the proton. Experiments on the ISR showed that quarks respond to the strong force as point-like particles. The fixed-target work on the SPS produced some very significant results (e.g. evidence of the nature of the interquark

FIG. F.1

NUMBER OF CERN USERS 1975 to 1985



force) despite the fact that this accelerator was completed four years later than a similar one in the United States. The conversion of the SPS to a proton-antiproton collider has led to CERN's greatest triumphs so far, namely the discovery of the W and Z vector bosons, in confirmation of major predictions of the electroweak theory, and the evidence it has obtained for the existence of the sixth or top quark. Appendix 10 lists the more important scientific results achieved at CERN.

F.16. In our examination of the standing of CERN we have found the first two of the recent papers by Irvine and Martin (ref 4) of value in providing background data on CERN and other HEPP laboratories but we think that their analysis of the data over simplified. The technical factors affecting the scientific performance of an accelerator, which are listed in their third paper (ref 4(III)), are common ground, but surely the success of a scientific venture is dependent on far more complex and interrelated factors and we are not persuaded that the methodology described has useful predictive value.

F.17. There is little doubt that CERN is one of the most successful European ventures; its scientific output has been outstanding, and it has been a pioneer in creating a truly international environment for research. We have been impressed by the enthusiasm for CERN displayed by physicists throughout Europe and in the US as well.

FUTURE FACILITIES AT CERN

F.18. The main future facility at CERN will be the large electron-positron collider LEP, which is currently being constructed over a period of eight years at a total materials cost of about £345M at 1984 prices. When it comes into operation in 1989, LEP will accelerate the electrons and positrons to 50 GeV. This will be 2 years later than the Stanford Linear Collider, which will also be an ee accelerator and which should have a similar centre-of-mass energy. Some evidence presented to us suggested that the earlier operation of the SLC would limit the scientific value of the LEP collider, but the situation is, however, not clear cut for reasons explained in C.16-C.18. The LEP collider is optimized to reach 100/100 Gev with an upper limit of 130/130 GeV. The overall cost of upgrading to 90/90 GeV which is now being considered would be £55M. Much of CERN's future programme is based on the assumption that this upgrading will be achieved fairly rapidly.

F.19. The LEP tunnel is sufficiently wide to accommodate a hadron collider should this be required (C.24). There is thus potential at CERN for creating new facilities to satisfy the likely experimental requirements into the next century.

THE CERN THEORY DIVISION

F.20. The Theory Division at CERN consists of about 21 staff members, of whom 7 physicists are on fixed-term contracts and the remainder are on indefinite contracts. In addition there are about the same number of CERN fellows from Member States and a larger number of visitors on sabbatical leave. In 1983, for example, there were at any given time about 60 visitors staying for at least two months, and about the same number staying for about one month.

F.21. The Theory Division is of undoubted high quality and provides important support to the experimental programme at the Laboratory. In addition it has also become a focus for European theoretical particle physics. All the British theoreticians we have met have stressed its value and many have spent one or more sabbatical periods there.

CERN AND EUROPEAN INDUSTRY

F.22. In paragraph D.15 we have already commented that in our opinion the benefits of spin-off from technology-based basic scientific research are often overstated. In this connection we have considered in some detail the effect of CERN on European industry in the light of letters we have received, including 18 from UK firms with contracts from CERN, and also of two surveys conducted by Schmied and co-workers (refs 5,6).

F.23. We are aware that CERN engineers have made a positive effort to involve European firms in development projects and that some UK firms clearly consider contracts with CERN to have been beneficial. Nevertheless, we have not seen any convincing evidence that the benefits are greater than could have been achieved as a result of a similar level of capital expenditure in other areas of well organized scientific, medical or engineering research. We therefore consider that its support for European industry cannot in itself be taken as a factor specifically favouring CERN above other technologically-based scientific enterprises.

F.24. The papers by Schmied et al attempt to quantify the benefits attributed to CERN, principally in the form of estimates of increased turnover amounting to about 60% of the cost of CERN during the period 1973-1982. In our view great care must be exercised over interpreting the value of increased turnover, because this is only one of a number of factors which determine the success of a company's activities, or benefits to European industry in general.

ORGANIZATION AND EFFICIENCY OF CERN

F.25. The governing body of CERN is the Council, which consists of two delegates from each Member State. The Council agrees the broad lines of research policy, approves the budget and manpower estimates, and appoints the senior staff. The delegations from Member States are of equal standing and major decisions are taken by a two-thirds majority, although there is a long-standing tradition that difficult issues are settled by seeking a consensus of opinion that can be supported by all the delegates. For the LEP construction period the voting requirements for the budget have been changed so that a unanimous decision is required to increase it above the 1982 level (adjusted for inflation). The Council receives advice on financial matters, including the budget and major contracts, from the Finance Committee, which consists of delegates from all Member States, again on an equal footing.

F.26. Advice to the Council on the scientific development of the Organization is given by the Science Policy Committee, which is made up of eminent scientists chosen in their own right rather than as delegates from Member States; in addition it includes as ex-officio members the chairmen of the European Committee for Future Accelerators (ECFA) and of the three CERN Experiments Committees. The latter committees, one each for the PS and SC, for the SPS and for the LEP, are responsible for reviewing the proposals made by physicists in Member States for experiments to be carried out on the CERN accelerators, and for making recommendations to the CERN Research Board, which is chaired by the Director General.

F.27. The day to day operation of the Laboratory is delegated to the Director General, who is supported by a directorate consisting of two directors of research who are usually appointed for a period of 3-6 years on secondment from universities in Member States, a director responsible for the LEP project, a technical director and a director of administration. Member States have recently shown their confidence in the administrative abilities of the present Director General by extending his normal 5 years appointment for a further period to cover the LEP construction. We have been impressed by the robust way in which he has organized the construction of LEP within the tight financial constraints set by the Council.

F.28. Just under half the CERN budget is spent on salaries and other personnel costs, and the remainder on capital projects, equipment, supplies and services. All important contracts for the supply of equipment and services are normally awarded after competitive tendering, from bids received from within Member States. The contract goes to the lowest bidder; in all but the smallest contracts, adjudication is on a basis of ex-works price, so that firms in distant member states do not suffer as a result of their higher transport costs. There is, rightly in our opinion, no principle of juste retour and hence costs are kept as low as possible.

F.29. It goes without saying that our knowledge of CERN is not detailed enough to enable us to form a view whether its organization could be improved and if so what specific changes would make it more efficient and more cost effective, and indeed given the present financial constraints we doubt whether more than minor economies could be achieved by this means. However, CERN has evolved rapidly from small beginnings and has undertaken major construction work; we think that the time is ripe for a review of its administrative structure. Efficiency audits by outside consultants have achieved significant savings in scientific institutions in a number of Member States, and we would recommend that the Council organize such an audit as part of its strategy for planning the structure of the Laboratory during the exploitation of LEP.

F.30. We have received views from witnesses in a number of Member States that the staff costs of the organization are too high, and that for some staff the salaries and allowances are generous even compared with the highest salaries paid for similar posts in national institutions in European countries. Not only is this a factor in the cost of the Organization, but also it causes difficulties in recruiting ex-members of staff to posts back in Member States. We are aware that in many areas CERN salaries and allowances are lower than in other international organizations employing scientists, but we think there is nevertheless scope for savings. The increasing importance of international collaboration means that it is essential for the cost of international organizations to be kept under close control.

THE FUNDING OF CERN DURING AND AFTER THE CONSTRUCTION OF LEP

F.31. In 1981 the CERN Council unanimously approved the construction of the LEP collider, with an initial energy of 51.5 GeV per beam at maximum luminosity and the development of 4 of the possible 8 interaction regions. The collider would use the existing PS and SPS accelerators as components of the injection system and would be constructed within a constant CERN budget of 617 MSF and a total materials cost not exceeding 950 MSF, both at 1981 prices. It was also agreed that any increase in the annual budget during the construction period would require the unanimous support of all Members, not just the usual two-thirds majority.

F.32. The financial constraints resulted in some reductions in staff (from 3622 to 3550), the closure of the ISR collider and of some of the fixed target facilities, a reduction of the SC operating hours from 6000 to 4000 per year, and negotiations with one of the electricity suppliers for a reduction in charges in return for an agreement that it could impose up to 22 days of power cuts at less than a day's notice.

F.33. The Council gave the CERN management complete flexibility over the use of the materials budget and staff deployment within broad guidelines concerning the reductions in facilities, and the management of CERN appear to have exercised the discretion given them in a most satisfactory manner. A small degree of overall flexibility in the budget has resulted from Spain rejoining the Organisation in 1983, as the Council agreed to use 60% of the gradually increasing Spanish subscription for new work (an increase to about 23MSF in 1988 at 1984 prices).

F.34. Figs F.2 and F.3 show the CERN materials budget and manpower levels since 1979 broken down by the major programmes. These diagrams, which were supplied by CERN, show the constant budget figures that have received initial approval from Council, i.e. those up to 1988, the last year of LEP construction: the extrapolations to 1990 have not yet been approved by Council and they are also based on the assumption of a constant budget. Note that the small increases in total budget shown in Fig F.3 are due to the gradually increasing Spanish contribution.

F.35. After the end of the LEP construction period in 1989 we understand that there will be three delayed commitments:

i. amortization of the underfunding of the CERN pension scheme (25MSF pa);

ii. repayment of the loan for the ACOL development (A total of 26MSF in 1989 and 1990);

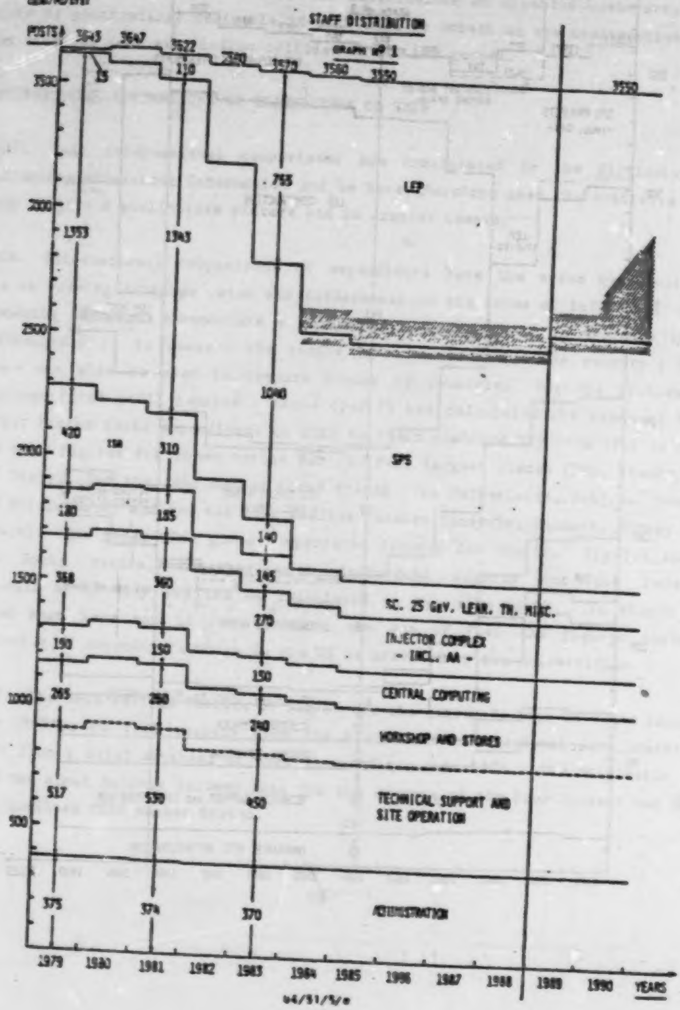
iii. refurbishment of the PS, which is an integral part of the pre-acceleration system for the SPS, and hence of LEP, and of other items the maintenance of which has been delayed during LEP construction.

These, together with the running cost of LEP, will to a certain extent offset the savings to be expected in both staff and materials, but only the first is a relatively long term commitment, and in total they should not make it impossible to achieve a significant reduction in the overall budget by the early 1990s.

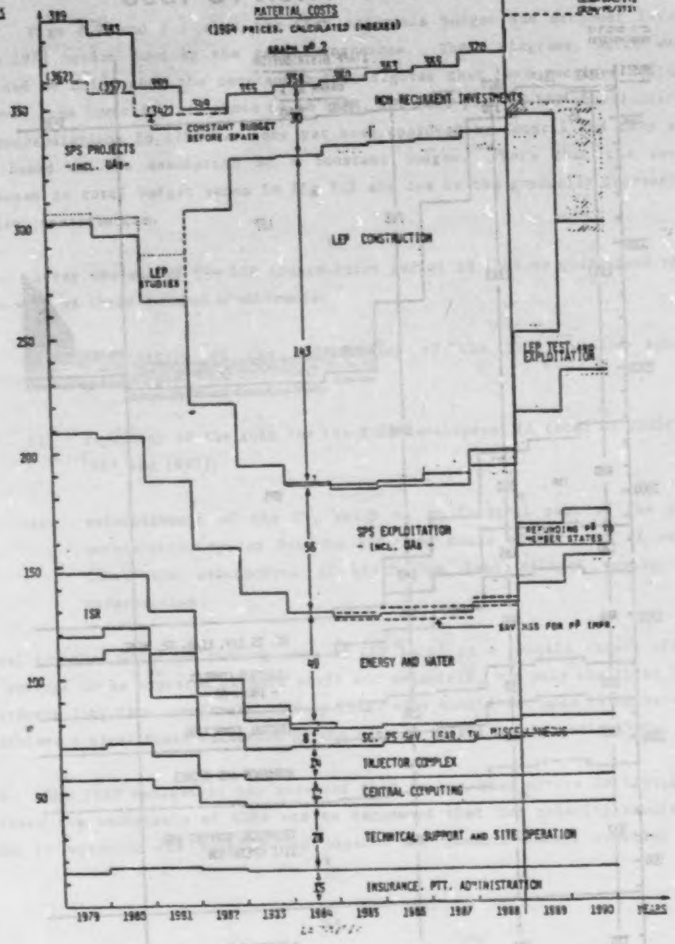
F.36. The CERN management has stressed that it has been active in trying to increase the membership of CERN and we recommend that top priority should be given to widening the subscription base. The Council should consider the

FIG. F.2

DISTRIBUTION OF CERN STAFF FROM 1979 to 1984 WITH PROJECTION TO 1990



DISTRIBUTION OF THE CERN MATERIALS BUDGET AT 1984 PRICES FROM 1979 to 1984 WITH PROJECTIONS TO 1990



possibility of introducing an intermediate status between that of observer and full membership for non-European States which wish to make more than just nominal use of the facilities. As explained in paragraph F.14, non-member states at present pay more per physicist than Member States towards the materials costs of experiments , but nevertheless an expanded membership base would be particularly desirable if CERN were to embark on the construction of a new machine, such as a hadron collider in the LEP tunnel.

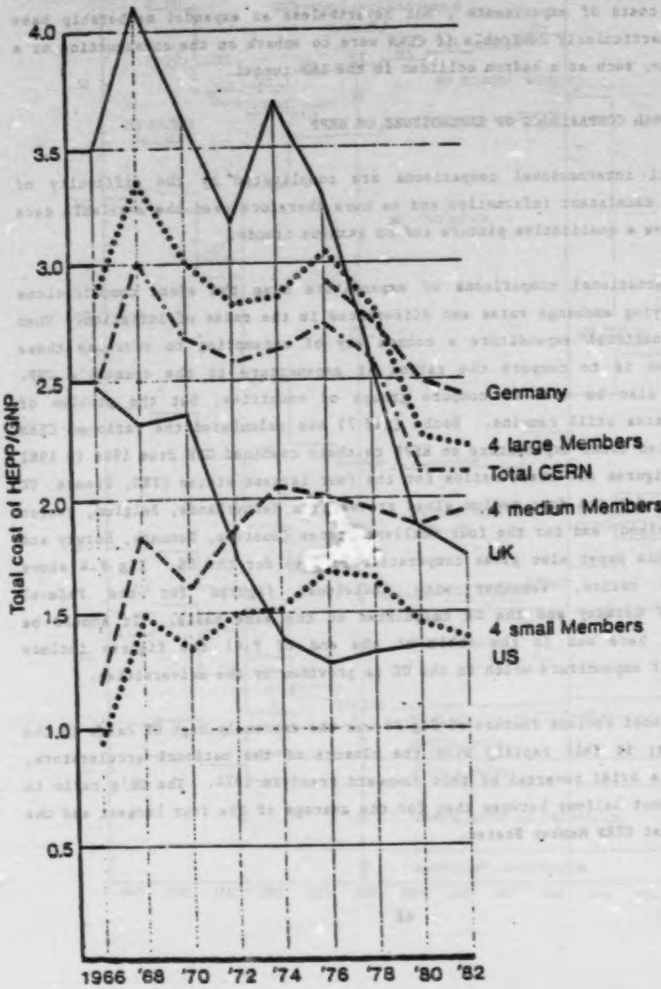
INTERNATIONAL COMPARISONS OF EXPENDITURE ON HEPP

F.37. All international comparisons are complicated by the difficulty of collecting consistent information and we have therefore used the available data only to give a qualitative picture and to examine trends.

F.38. International comparisons of expenditure have the added complications due to varying exchange rates and differences in the rates of inflation. When comparing national expenditure a common way of attempting to overcome these difficulties is to compare the ratios of expenditure to the country's GNP. These can also be used to compare groups of countries, but the problem of exchange rates still remains. Roche (ref 7) has calculated the ratio of CERN Member States total expenditure on HEPP to their combined GNP from 1966 to 1982 and gave figures for these ratios for the four largest states (FRG, France, UK and Italy), for the four medium sized states (The Netherlands, Belgium, Sweden and Switzerland) and for the four smallest states (Austria, Denmark, Norway and Greece). His paper also gives comparative figures for the US. Fig F.4 shows the Roche ratios, together with individual figures for the Federal Republic of Germany and the UK calculated on the same basis. It should be noted that here and in the table at the end of F.41 the figures include estimates of expenditure which in the UK is provided by the universities.

F.39. The most obvious feature of Fig F4 was the extremely high UK ratio in the late 1960's; it fell rapidly with the closure of the national accelerators, apart from a brief reversal of this downward trend in 1974. The UK's ratio in 1982 was about halfway between that for the average of the four largest and the four smallest CERN Member States.

THE RATIO OF TOTAL COST OF HEPP TO GNP FOR VARIOUS GROUPINGS OF CERN MEMBER STATES & INDIVIDUALLY FOR FRG, UK & THE US BETWEEN 1966 & 1982



F.40. The fall in the UK figure was obviously a factor in the small overall decline in the European ratio ("Total CERN"), but the other important feature is the present relatively high ratio for Europe compared with that for the US. In 1966 the ratios were comparable, but by 1975 the European ratio was double that of the US. Since that time the difference has decreased, and if the US were to embark on the construction of the SSC the ratios would again be similar on present cost estimates. On other methods of comparison the US figures are not so low, as can be seen from the following comparative data for 1982 using an exchange rate based on purchasing power:

		UK	Europe	US
Total cost of HEPP	£M	46	320	250
Cost/physicist	£M	0.14	0.14	0.19
Cost/inhabitant	£	0.85	1.1	1.1
Cost/GNP 10^{-4}		1.8	2.1	1.4

THE UK SUBSCRIPTION

F.41. Article VII (b) of the CERN Convention requires the Council to decide every 3 years the scale of contributions of Member States, based on the average net national income (NNI) at factor cost for the 3 latest years for which statistics are available. The latest determination was in September 1983 for the years 1984, 1985 and 1986, and was based on the NNI figures provided by the UN Statistical Office for the years 1979 - 1981. For 1985 the distribution of the cost of CERN between member states is as follows:-

	%		%
Austria	2.37	The Netherlands	5.67
Belgium	3.93	Norway	1.74
Denmark	2.09	Spain	1.31[1]
France	20.60	Sweden	4.04
FRG	24.67[2]	Switzerland	3.86
Greece	0.40	UK	16.07
Italy	13.28		

[1] Special rate for an initial period (increasing each year to 1988)
[2] Reduced rate due to the "ceiling" of 25% specified in the Convention.

F.42. Table FII analyses the UK subscription at both current and 1984 prices between the years 1975 and 1984. Over this period the CERN budget and the UK subscription have both decreased by about 20 per cent in real terms but, as can be seen from Fig F.5, the cost of the UK subscription in sterling decreasedmuch more rapidly than this between 1978 and 1981 and since then has started to increase again. The fall in the CERN budget as a whole from 1975 to 1981 was mainly due to the reduction in capital spending at the Laboratory after the completion of the SPS, and as explained above the budget has been kept constant in real terms from 1981, and will continue at the same level until 1989. Between 1975 and 1978 the benefit to the UK of the reduced CERN budget was lost by the fall in the value of sterling. The dramatic fall in the cost of the subscription between 1978 and 1981 was the effect of a reduction in the UK's share of the budget at a time when the value of sterling remained relatively constant, but after 1981 the falling exchange rate and, in 1983, the increase in the UK's share of the budget from 14.1% to 16.1%, have resulted in a £8M rise in the cost of the CERN subscription.

F.43. The combined effect of changes in the UK's percentage share of the CERN budget and of fluctuations in the Swiss franc/pound exchange rate have caused extreme difficulties to the SERC, making efficient advanced planning of the Council's budget impossible. Over the past decade yearly fluctuations from the estimate figure due to exchange variations have been as great as £8M, but the net effect in the same period was only £5M. It would therefore seem sensible for some mechanism to be found to even out these variations; we discuss this further in Section H.

Table 7.1

ESTIMATED CONTRIBUTIONS TO THE MATERIALS COST OF LEP EXPERIMENTS IN M SWISS[1] FRANCS

	ALEPH	DELPHI	OPAL	L3	Total	%
Austria		1.00			1.00	.30
Belgium		1.80			1.80	.53
Denmark	.52	.50			1.02	.30
France	10.20	12.50	3.00	4.50	30.20	8.97
FRG	9.29	5.00	7.50	8.00	29.79	8.85
Greece		1.00			1.00	.30
Italy	12.00	10.50	1.80	6.00	30.30	9.00
Netherlands		3.00		3.00	6.00	1.78
Norway		1.50			1.50	.45
Spain		2.50		6.00	8.50	2.52
Sweden		2.50			2.80	.83
Switzerland				17.00	17.00	5.05
UK	10.60	6.60	10.50		27.70	8.23
CERN	13.60	17.00	11.00	8.50	50.10	14.88
Total (Member States)	56.21	65.70	33.80	53.00	208.70	62.00
Canada			6.00		6.00	1.78
China	2.00			2.00	4.00	1.19
DRG				2.00	2.00	.59
India				1.00	1.00	.30
Israel			1.40		1.40	.42
Japan			21.60		21.60	6.42
Poland		.50			.50	.15
USA	3.00	3.50	8.50	48.10	63.10	18.74
USSR		8.00		20.40	28.40	8.43
Total (Non-Member States)	5.00	12.00	37.50	73.50	128.00	38.00
TOTAL	61.21	77.70	71.30	126.50	336.71	100.00

[1] From CERN/FC12801

Note that there might be slight variations in the exchange rates used by the various collaborations when calculating the figures for this table. At January 1983 prices the budgetary allocations for the UK share of the materials cost of three LEP experiments are:-

ALEPH	£3.4M
DELPHI	£2.1M
OPAL	£3.5M

FIG. F.5

THE CERN BUDGET AND UK SUBSCRIPTION FROM 1975 TO 1984 IN MILLIONS OF SWISS FRANCS AND £M. RESPECTIVELY (Note different scales)

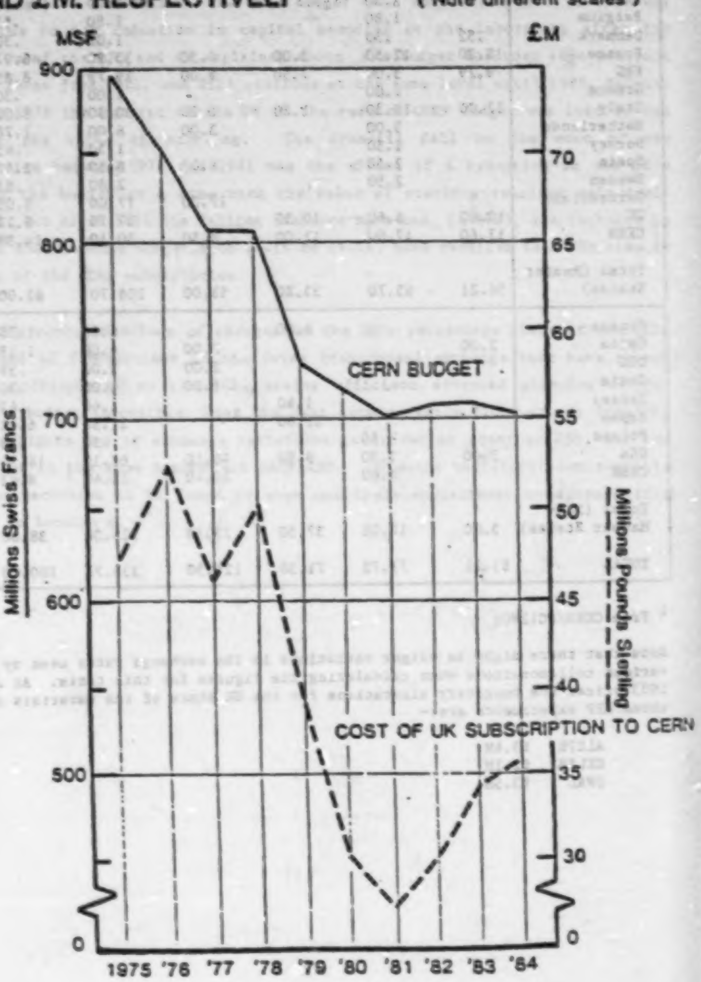


TABLE F.II

THE CERN BUDGET AND THE UK SUBSCRIPTION 1975-1984

Year	CERN Budget (MSF)[1] Cash	CERN Budget (MSF)[1] 1984 prices	UK% of[1] CERN	Exchange rate	UK Sub[2] (£M)[2] Cash	UK Sub[2] (£M)[2] 1984 prices	% of SERC
1975	669	897	16.4	5.5	18.6	47	17.2
1976	674	853	16.4	4.5	23.2	52	18.2
1977	646	805	16.4	4.1	23.8	46	17.0
1978	643	806	15.8	3.4	27.7	50	17.2
1979	601	733	15.8	3.6	25.2	39	13.9
1980	600	716	15.8	4.0	22.4	30	10.8
1981	614	701	14.1	3.9	22.5	27	10.8
1982	646	698	14.1	3.4	26.6	30	10.9
1983	686	706	14.0	3.1	32.1	34	12.6
1984	701	701	16.1	3.1	35.5	35.5	12.7

CERN budget for calendar year

UK subscription for the financial year 1 April to 31 March

G THE OPPORTUNITY COST OF HEPP WITHIN THE SCIENCE BUDGET

G.1. It was clearly not possible within the scope of our review to make a study in depth of the opportunity cost of HEPP research within the Science budget, so we decided to limit ourselves to an overview of the situation by meeting the Heads of Research Councils and by inviting evidence from the CVCP and the Royal Society. In addition we have received a range of written evidence on this aspect of the review and have supplemented this with discussions with scientists in fields other than particle physics.

G.2. In these discussions we have found evidence of considerable under-funding of important areas of scientific and engineering research and of the consequential low morale that pervades every branch of research. As indicated above, we have been unable to study this situation in detail, and even if this had been possible, we would not have presumed to do the work of the ABRC and the Research Councils in preparing a list of research topics in order of priority. Nevertheless, we are persuaded that there are very important areas where there are urgent funding problems. We have attempted to weigh these against the expenditure on particle physics.

G.3. We were particularly impressed by the evidence from the CVCP that long-term damage is being done to university research by the high rejection rate of top quality research proposals, and also by the critical state of laboratory instrumentation, which in many areas is now totally inadequate. This applies both to equipment that would normally be provided by the university from its UGC grant to form part of a "well found laboratory", and also to the replacement of ageing and obsolete equipment provided by the Research Councils. The damage extends to areas covered by all the Research Councils and is having an effect not only on university research, but also on teaching. The situation is especially acute in mainstream physics and chemistry, and this is particularly worrying because of the importance of these subjects for the underpinning of many science-based industries and for the provision of trained manpower.

G.4. The Heads of the Research Councils have identified areas that they considered to be especially underfunded. In addition it is clear that even some of our very best laboratories urgently need additional funds to equip them to world class standards and to allow them to remain at the forefront of their subject. We are pleased to note that the situation is being slightly ameliorated by the selective distribution of an additional £4M, but much more is required.

G.5. Our discussions with the Heads of the Research Councils took place while their organizations were at an early stage of the 1985 Forward Look exercise and before their Councils had had a chance to study the effect on their programmes of the increase in the Science budget announced in December 1984. Nevertheless, they were able to give a broad outline of problems facing their Councils and to discuss what they regarded as the top priority areas that could benefit from increased funding. While this identified areas where any savings from the present expenditure on HEPP might in principle be spent and hence made possible some form of comparison, we did not take it upon ourselves to explore in any detail possible areas for savings within the Research Councils' responsibilities that might be accorded lower priority than some or all aspects of HEPP. However, it was apparent that all the research councils are under severe financial pressure.

G.6. Before considering separately the situation within the areas covered by each of the Research Councils, it is useful to set out the 1984/85 allocations to particle physics and to the five Councils, the percentage of the science budget allocated to each activity, and the Research Councils' total income including commissioned research.

	Grant-in-aid £m	% of Science budget	Total Income[1] £m
Particle physics	35.1	10.1	–
AFRC	46.5	8.5	103.5
ESRC	22.0	4.0	22.5
MRC	117.2	21.5	123.9
NERC	65.9	12.1	90.5
SERC[2]	278.8	51.1	288.1
Others	15.2		
Total Science budget	545.6		

[1] Including income from other Government departments.

[2] Including particle physics

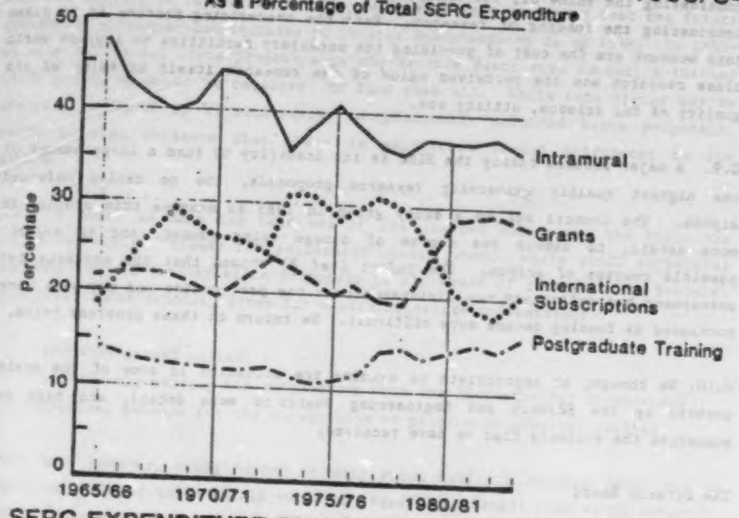
SCIENCE AND ENGINEERING RESEARCH COUNCIL (SERC)

G.7. The SERC is by far the largest Research Council in terms of its expenditure, the scope of its activities and the size of its community. It is responsible for supporting those areas of basic science and engineering not covered by the more specialized Research Councils. Most of the research it supports is undertaken at universities and other institutions of higher education, but the Council also maintains two major laboratories which provide facilities for university research workers, the Rutherford Appleton Laboratory and the Daresbury Laboratory, and two UK observatories and their overseas outstations. It is also responsible for paying the subscriptions to seven international facilities at a total cost of £52.2M, and the cost of these subscriptions is so large that exchange variations can have a significant effect on the overall programme. Figure G.1(a) shows how the proportions of SERC funds spent on in-house facilities, on international subscriptions, on university grants and on postgraduate training have varied over the past 20 years. As can be seen the relative fall in the proportion of international subscriptions has been taken up mainly by university grants, and Fig G.1(b) shows that it is the Engineering Board and to a lesser extent the Science Board which have benefited. In the case of the Science Board the steep rise in 1979-80 was a special once-off exercise to improve equipment. The upturn since 1982-83 in international subscriptions is due to the recent fall in the value of sterling coupled with increases in the UK share of the cost of CERN (and the European Space Agency) resulting from the rise in the relative GNP in the late 1970s (as explained in Section F). These two factors increased the proportion of the budget allocated to the Nuclear Physics Board.

G.8. Table G.1. shows SERC's estimate of the relative sizes of the communities which look to the respective SERC Boards for support together with the numbers of principal SERC grant holders and of SERC research and advanced course students, on the dates indicated (which are the latest for which figures are available). The table also gives the total allocation to each Board expressed as an average per academic staff member and per research student in the areas covered by each Board. The relatively high unit costs for the "large sciences" follow from the combination of the expensive facilities and the small number of scientists involved - in these areas there has already been a policy of

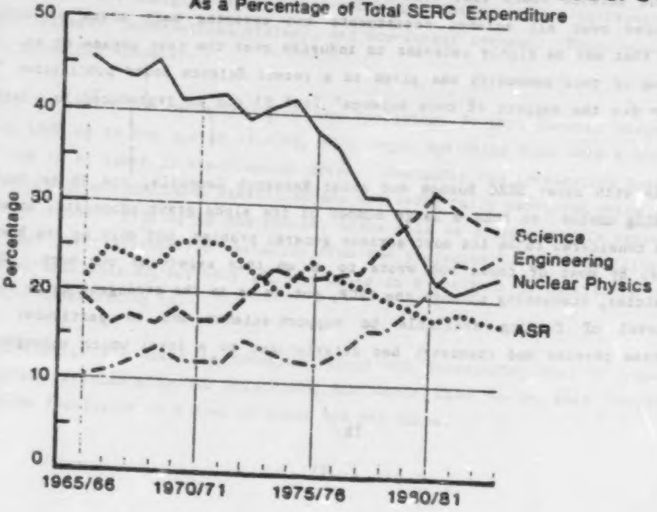
a. SERC EXPENDITURE BY CATEGORY 1965/66-1983/84

As a Percentage of Total SERC Expenditure



b. SERC EXPENDITURE BY BOARD 1965/66-1983/84

As a Percentage of Total SERC Expenditure



concentrating resources at a few universities. Unit costs have a role when considering the value of, for example, post graduate training, but less so when considering the funding of research. Here the over-riding factors to be taken into account are the cost of providing the necessary facilities to support world class research and the perceived value of the research itself in terms of the quality of the science, utility etc.

G.9. A major problem facing the SERC is its inability to fund a large number of the highest quality university research proposals, the so called unfunded alphas. The Council set up a study group in 1983 to examine this problem in more detail, to assess the degree of damage being caused, and to suggest possible courses of action. The report (ref 8) showed that the criteria for assessment had definitely not diminished over the past decade and may well have increased as funding became more difficult. We return to these problems below.

G.10. We thought it appropriate to examine the situation in some of the areas covered by the Science and Engineering Boards in more detail, and here we summarize the evidence that we have received.

The Science Board

G.11. The Science Board (SB) relates to a community of over 6,500 academics distributed over all science departments and covering many areas of basic science that may be highly relevant to industry over the next decade or so. A breakdown of this community was given in a recent Science Board publication "A strategy for the support of core science" (ref 9) and is reproduced in Table G.II.

G.12. As with other SERC Boards and other Research Councils, the SB is faced with being unable to fund a large number of its alpha grant proposals, indeed this is considered to be its most serious general problem, not only by the Board but also by most of those who wrote to us on this aspect of our work. The universities, commenting through the CVCP, put to us in the strongest terms that the level of funding available to support science and in particular in mainstream physics and chemistry has deteriorated to a level which endangered the continuing success, as judged by the highest international standards, of even the leading UK laboratories. They were also very concerned that the future quality of education and training in physics and chemistry is at risk. In 1983-84 only 74% of all alpha proposals to the Science Board were funded; a further £8.5M per annum would be required to fund them all. While this figure may be somewhat inflated by re-submissions of previously unfunded alpha proposals, there is also evidence that there is suppressed demand attributed to low morale.

G.13. In order to make the best use of its limited resources, the Board has identified certain themes for particular encouragement, while still supporting the very highest quality alpha proposals in all areas of research. It has also identified three priority areas for multidisciplinary initiatives:

low-dimensional solids;
protein engineering (in conjunction with the Biotechnology Directorate);
chemical sensors for the recognition of particular chemical species.

These are, however, being funded at only about half the optimum level and an additional £3M per annum in all would be required to handle them satisfactorily. Still other new interdisciplinary topics that may have important industrial applications are emerging, such as molecular electronics, molecular recognition, neurochemistry, mathematical biology, and non-linear systems. These would each cost about £2M annually.

G.14. The Board is concerned that the Spallation Neutron Source, which cost about £50M up to the end of 1984/85, will begin operating with only 6 out of a maximum of at least 22 experimental areas. Similarly the Synchrotron Radiation Source (SRS) and the laser facilities are not being fully exploited owing to the lack of funds. Looking to the future, there will be a considerable demand for the high power synchrotron radiation from the projected European facility that will be available if, but only if, the UK is in a position to contribute to the cost of constructing it.

G.15. Finally the Board is concerned about the inadequate level of computing resources available to UK scientists and would wish to be able to provide enhanced facilities at a cost of about £1M per annum.

The Engineering Board

G.16. The Engineering Board also faces the problem of unfunded alpha proposals. This is inhibiting research in all the main engineering disciplines and it is a constraint on the development of the fastest moving fields, such as materials, information technology and the application of computers to all areas of engineering.

G.17. In view of the present limited ability to fund university grants, the Board has had to impose a moratorium on the approval of new promoted coordinated programmes (Specially Promoted Programmes - SPP) which are undertaken to stimulate the community with the aim inter alia of increasing the level of research and throughput of manpower in priority topics in selected areas.

G.18. The Board also expressed concern at the inadequate level of funding that had been made available to support the Alvey programme, falling significantly below the £50M envisaged at the start. This shortfall coincides with a forced reduction in the support for non-Alvey information technology research. To give an impression of the magnitude of the problems encountered, we were told that a single sub-committee of the Information Engineering Committee, the Solid State Sub-committee, is experiencing a shortfall of funding for highest quality research initiatives - those judged to be creative, innovative and applicable-of the order of £8M per annum. The shortage is felt equally sharply in the programme of two major directorates, Biotechnology and ACME (The application of computers to manufacturing engineering).

MEDICAL RESEARCH COUNCIL (MRC)

G.19 About 40% of the MRC's funds are used to sponsor paramedical and biological research at universities, and the remainder to support its institutes and units. There are only three major institutes - the National Institute of Medical Research (NIMR), the Clinical Research Centre (CRC) and the Laboratory of Molecular Biology (LMB) - the 60 units being smaller and, like the LMB, mainly connected with universities. The units provide some measure of flexibility, since the continued need for a particular unit is always reassessed when its Director leaves or retires, and since 1976 the Council has closed 20 existing units and created 14 new ones.

G.20. Support to the MRC from the Science Budget has been reduced by about £4M per annum since 1983 and now the Council is only able to fund just over 50% of the highest quality university proposals. This has resulted in its not being able to continue the support of some very high quality university groups.

G.21. The social implications of much medical research make it particularly difficult for MRC to apply a policy of selectivity based purely on the quality of the work. Indeed we were told that it is almost impossible for it to cease funding any area of medical research, and this, of course, reduces its ability to support new initiatives.

G.22. Any additional funds that could be made available would be used to increase the number of university groups funded, to establish units for the clinical applications of molecular biology, neurobiology and protein engineering, and to increase the Council's support of NMR and positron imaging.

AGRICULTURAL & FOOD RESEARCH COUNCIL (AFRC)

G.23. The AFRC had been planning for a reduction in its budget of about £7M by 1988, due to the combined effects of reductions in grant-in-aid from the Science budget, reductions in commissioned work from the Ministry of Agriculture Fisheries and Food (MAFF) and the Scottish office (DAFS), and increased provision for superannuation. During the same period it was planning for reorganization and for new initiatives which would themselves cost an additional £7M per annum. The Council had estimated that to accommodate these cuts and the new research would require a reorganization of its institutes and the loss of about 1,200 jobs. Since these plans were made, MAFF has announced that its R and D budget will be reduced by £10M in 1986/87 and £20M in the following year and, although it is not known how much this will effect commissioned work at AFRC, further reductions in manpower and other rationalizations within the Council will certainly be necessary.

G.24. The bulk of the research funded by the AFRC is carried out at institutes either owned or grant-aided by the Council, many of which it inherited when it was founded in 1931. The Council also supports university research, but permanent institutes are necessary for long-term experimental programmes that have to be independent of the individual scientists involved. Apart from the loss of existing staff indicated above, the Council intends to increase flexibility by making more fixed term appointments, especially for contract work, and also by increasing the proportion of research carried out through universities.

G.25. Prior to the announcement of major reductions in the research and development budget of the MAFF, the AFRC had indicated that an injection of about £4M per annum would be needed to allow it to increase its work in the following high priority areas: plant biotechnology (£1M), food biotechnology (£0.25M), vaccine production (£1M), endocrinology (£0.75M), and cell biology (£0.75M).

THE NATURAL ENVIRONMENT RESEARCH COUNCIL (NERC)

G.26. Like the AFRC, much of the NERC's research is carried in its own institutions and it too has recently had substantial cuts in its commissioned research. Thus it also is faced with the need to reduce staff and to bear the associated non-recurrent redundancy costs. The NERC Corporate Plan 1985-90, published in February 1985, stated that the Council intended to reduce its present 3130 staff to about 2200 by 1989-90. It would also transfer some of its research activities to universities and increase the proportion of staff on fixed-term contracts.

G.27. The Council hopes to retain a presence in most major areas of environmental research and to initiate some new work in high priority areas including deep crustal drilling (£5-10M for a 3 km borehole, £20-25M for an 8-10 km borehole), the development of a remotely controlled submersible for deep ocean work (£2M), and the provision of a remote-sensing altimetry satellite (£18M over 10 years) as well as to continue UK participation in the Ocean Drilling Programme (ODP) (£1.5M per annum).

G.28. It is clear that, as with the AFRC, the NERC is faced with major financial difficulties, and that the sudden reduction of contract work at too short notice to allow rational restructuring of the Council's institutes has led to significant redundancy costs. Both Councils will have to bear these costs, unless they are shared by all the Research Councils, and in any event the funds available for science will be reduced.

THE ECONOMIC AND SOCIAL RESEARCH COUNCIL (ESRC)

.29. Apart from the impact of inflation on the allocation to the ESRC, in
ommon with other Research Councils, ESRC has suffered cuts of more than 30% in
eal terms since 1978. The full impact of these cuts has fallen on post-
raduate training, and now leaves the Council exposed to the criticism from the
C that "funding (of post-graduate students) is now inadequate to enable (the
RC) to play the proper role of a Research Council in support of research
aining" (UGC Strategy document).

30. Research has been protected but the success rate in the responsive
earch Grants Scheme has fallen severely as funds have been switched to
earch initiatives sponsored by Council. In particular the ESRC is giving
h priority to the study of industrial innovation. Important areas are the
nomic and managerial implications of information and communications
nology; the competitiveness of British industry; and ESRC's contribution to
SERC's Teaching Company Scheme.

ORGANIZATION OF SCIENTIFIC RESEARCH

. We agree that all UK scientists should be free to make proposals to
Research Councils for support and that, in relatively inexpensive areas of
rch, decisions should be taken on the quality of the proposal judged purely
ientific merit. However, in areas where major supporting facilities are
red difficult decisions will have to be taken on wider criteria. In
on B we have suggested that the probability of early application should be
f these criteria and that in the present financial situation we believe
ome redistribution of funds should be made towards those areas of science
to underpin future science-based industries. In this situation the UK
satisfactorily participate in all fields of research, and in expensive
of basic science there is a good case for concentrating on those fields
research of world class standard is being achieved.

ccess to adequate funding does not guarantee success in scientific
h; we are also concerned about the apparent shortage of suitable research

scientists and engineers in certain fields. In some cases the problem is exacerbated by expertise being spread too thinly across the universities. Thus both financial and manpower arguments lead us to believe that there should be a rationalization of scientific and engineering research in this country. We also believe that there are problems at the interface between basic and applied science and at that between academic research groups and industry. We accordingly recommend that there should be a joint ABRC, ACARD investigation into this area and that it should also look into the coordination of funding derived from different Government sources.

TABLE G.I

MANPOWER NUMBERS AND FINANCE ASSOCIATED WITH THE SERC BOARDS

	ASRB[1]	EB[2]	NPB[3]	SB[4]	TOTAL
Expenditure (1983-84)(£M)	42.7	63.4	56.1	69.8	254.3[5]
Size of Community: (1982)					
Academic staff	270	4070	326	6563	11229
RAs/Fellow	350	2507	180	1626	4623
Research Students	280	5928	334	9596	16138
SERC Students (Nov 1983)					
Research Students	222	2481	180	3744	
Advanced Students	27	1455		344	
SERC Principal grant holders (August 1984)	178	1566	82	1329	3155
Ratio of expenditure to size of community					
academic staff (£K)	160	16	170	11	23
research student (£K)	150	11	170	7	16

1. Astronomy, Space and Radio Board
2. Engineering Board
3. Nuclear Physics Board including nuclear structure and particle physics
4. Science Board
5. Total SERC expenditure including central support and administration.

TABLE G.II

THE SCIENCE BOARD'S ACADEMIC COMMUNITY[1]

	Academic staff	SERC fellows	Other SERC supported researchers	Research Students SERC	Research Students Total
Biological Sciences	2200	63	584	1384	3450
Chemistry	1660	37	477	1426	2600
Mathematics	1700	19	110	365	1850
Physics[2]	1100	13	303	496	1750
TOTAL	6600	132	1474	3671	9650

[1] From ref 9

[2] Does not include physicists funded by the Nuclear Physics or Astronomy, Space and Radio Boards.

E. CONCLUSIONS

E.1. The Group recommends that the UK should remain a Member State of CERN on the present basis until 1989, but that it should continue its membership beyond that time only if this can be achieved at a significantly lower cost.

E.2. We have been greatly impressed by the exciting stage of development that has been reached in particle physics, by the standard of the research undertaken by UK physicists, and by the excellence of the available and projected facilities both at CERN and at DESY. UK particle physicists are clearly playing a full part in research of world class standard and there are good prospects of this continuing into the foreseeable future. We believe that the subject is worth pursuing in the long term and hence that the UK should continue to play an effective role in experimental as well as theoretical research. However we also believe that with the present resources available for science in the UK, and taking into account other areas of research that are underfunded or even having to be forgone, the current level of expenditure by the UK on particle physics cannot be justified and should be reduced as rapidly as possible. Indeed, at any realistic level of the SERC budget the proportion now taken up by particle physics is too high.

E.3. CERN is at present the leading particle physics laboratory in the world and is an inspiring example of what can be achieved by European collaboration. We believe that British withdrawal from CERN would be a major blow to the science both of the UK and of the rest of Europe, and that it would have long term detrimental implications for international collaboration. This would be particularly so if the withdrawal took place during the period of construction of the LEP.

E.4. The speed with which savings can be achieved is limited by the present LEP construction programme at CERN and thus, for reasons explained in more detail below, we recommend a progressive reduction in the UK total expenditure on particle physics that would be modest up to 1988/89, but would then increase to at least 25% by 1991. In our view, the recommended reductions in the cost of CERN to existing Member States starting in 1987/88 would represent an attainable adjustment coming as they would after the end of a major construction phase, and that they would still allow the Laboratory to maintain itself at a world class standard albeit at a reduced pace of development. The recommended reduction in the domestic expenditure would require a significant decrease in the size of the experimental community, but should permit an orderly contraction and maintain an appropriate UK contribution to the field.

H.5. The above conclusions have been reached in the light of the financial circumstances of the UK, although indeed these may not be unique amongst CERN Member States. We do, however, believe that irrespective of the present acute financial situation the overall level of expenditure on the subject is too high, and therefore that the pace of major capital expenditure at CERN should be reduced by extending the periods between upgrades or between new machines. Indeed, we believe that in view of the high cost of the research, and the possibility of new techniques being developed for accelerating particles, it would not be counter to the long term interests of the field if the pace could be reduced world wide and not merely at CERN.

REDUCTIONS IN EXPENDITURE ON PARTICLE PHYSICS

H.6. As indicated above we consider that there should be a decrease in the pace of further major capital developments after LEP. This would, however, only achieve savings in the next decade and the UK has major problems now. In evaluating possible ways of reducing the overall cost of particle physics to the UK we have taken into account the following considerations.

i. We have noted that the overall budget of CERN has declined by about 20% in real terms over the past decade, and that the funding of particle physics in the UK excluding the CERN subscription has declined over the same period from what was an extraordinarily high level by about 55% during the same period (or 35% if the operating costs of NINA and NIMROD are excluded). We are satisfied that now in particle physics, as in other areas of UK science, there are first-class research proposals that are not being funded and important experiments that are being terminated prematurely.

ii. To undertake particle physics at an effective level requires a large initial outlay and it is not worth making this investment unless the research carried out is of the highest quality. From this it follows that:

a. it is important to ensure that CERN is able to maintain world class facilities;

b. there must be sufficient domestic funds for UK physicists to contribute effectively to the research.

iii. We have considered the background to the 1981 "gentlemen's agreement" about the funding of LEP, outlined in paragraph F.7. We do not think that either of the conditions put forward by the UK delegate at that time could reasonably be invoked as a reason why the UK would now have to consider withdrawing from CERN. Hence we believe that the UK has a strong moral obligation to remain a member of CERN at least until the end of 1989, when the majority of the contracts will be completed.

iv. UK groups are committed to the construction of major components for three of the four LEP detectors. If the UK were to cease funding these components, the three collaborations involved would be faced with major delays in the installation of the detectors, even if alternative sources of funds could be found to make up for the UK contribution.

v. The commitment to the three LEP detectors limits the rate of possible savings in the domestic budget.

vi. It is important that the timing of any reductions should be such that, as far as possible, any necessary decrease in the number of experimental particle physicists should be achieved in an orderly fashion and in such a way that those remaining are chosen on merit.

H.7. We have indicated in Section F that we consider the UK should press the CERN Council to undertake an immediate review of the future financial structure of CERN once the LEP collider is in operation, and that we would expect a significant fall in the budget of the Laboratory after 1989. We think that it should already be possible to make some savings in personnel costs before that date. We therefore recommend that the UK give immediate notice to the CERN Council that it will be unable to continue the present level of its subscription after the end of the LEP construction, and that it would be looking for successive reductions in its subscription of, say, 5% in 1988-89 rising to a total of 25% in 1991. We believe that these represent the minimum reductions in the UK's commitment that could justify our continued membership of CERN beyond 1989. This reduction could be achieved by a combination of a reduced CERN budget and of additional sources of income, possibly through the introduction of an intermediate form of membership for non-European states.

H.8. We recommend that the total domestic expenditure on particle physics be progressively decreased, attaining a reduction of 25% by 1990/91 on the centre line figure of about £20m (excluding research students and HQ overheads) used for the 1985 forward look exercise, in such a way that the UK is able to honour its commitments to one of the major experiments on the CERN proton-antiproton collider (UA1) and three LEP experiments, and in addition to make a contribution to one experiment on HERA. This level of expenditure should enable support of the three LEP experiments to be continued into the next decade, but we appreciate that if significant up-grades proved necessary after 1989 the UK might not be able to continue supporting all three detectors. The Particle Physics Committee should draw up plans for rationalizing its support of the present particle physics community, for example by reducing the number of universities receiving it, by concentrating the support staff at fewer universities, and by optimizing the balance between support staff at universities and at RAL.

H.9. The reductions that we recommend could be achieved in a number of ways. One of these is illustrated in table H.1, giving overall savings over the years 1986/7 to 1992/93 totalling £55.8m, an average of about 14% per year. However, our recommendations on the level of saving required by 1991 cannot be achieved easily either at CERN or within the UK domestic programme. We have therefore deliberately refrained from making detailed recommendations that would reduce the options available to the various decision-making bodies.

THE SCIENCE BUDGET

E.10. We are aware of the fact that savings of this order cannot be achieved without considerable disruption and, indeed, pain. It is our general perception of the inadequate level of funding in other branches of pure and applied science that has led us to recommend these measures; the savings which our proposals would generate represent only a small contribution to the solution of the UK science research funding problem, however we believe that the measures we recommend would be justified even if it were possible to anticipate some increase in the total UK Science budget.

E.11. We are also very conscious of the fact that the savings that we have advocated could easily be eroded if the Science budget were not properly indexed to cover the following items:

i. the general level of inflation;

ii. the increases in international subscriptions due only to changes in relative GNP and exchange rates.(i.e. non-volume changes); suitable mechanisms need to be found for correctly adjusting the Estimate for a particular year to take into account non-volume changes, and to cover exchange rate variations during the year.

E.12. On the question of general indexing of the Science budget the Government has indicated its intention to maintain the budget in "real terms", and in 1985/6 did indeed achieve this. With regard to international subscriptions, most are based on relative GNP calculations which in turn are dependent on exchange rates. Over a decade or so the overall effect may be small, but the short term effect on the Science budget, and in particular on the SERC, can be significant. We strongly recommend, in the interests of rational and effective management of resources, that suitable arrangements be made with the Treasury for full indexing of non-volume changes which will, of course, involve surrender of any windfall gains from such exchanges. Changes in subscriptions due to increased activity would remain the responsibility of the relevant Research Council, which should also be able to make alternative use of savings due to educed activity.

E.13. We have been impressed by the wide range of important research fields that are in urgent need of additional resources and we are conscious that, because of prior agreements, our recommendations for particle physcis would not release significant sums of money in the early years. We would again emphasize that an eventual saving of 25% on particle physics expenditure would not in itself solve the financial problems of other areas of science; but it would in our view balance the advantages of continuing effective research in particle physics and of at least making a partial contribution to the needs of other areas of science. We would recommend that over the next few years the organization of science in the UK should be rationalized to ensure that the funds available are used more effectively, but we recognize that additional funding, above that now expected for the Science budget, will be required in the short term, if the UK research base is to meet the challenges of the next decade.

INTERNATIONAL COLLABORATION

E.14. In several places in this report we have stressed our conviction that the UK should continue to play its full role in international scientific ventures while at the same time we have emphasised the need to ensure that such activities are effectively controlled by the participating countries and that they are efficiently run. We are concerned that the SERC at present sees little scope for adequate participation in the proposed European synchrotron radiation facility or the spallation neutron source, each of which would provide important facilities to UK scientists in the next decade, and that at the same time it is unable to fund its own existing facilities in these areas at a level that attracts the optimum number of international collaborators. Funds are needed for such ventures, but we would reiterate our comments in section F that it is essential for a mechanism to be devised to ensure that increased costs due to exchange rate variations or changes in relative GNP do not jeopardize other parts of the science programme.

E.15. The scale of these international projects, and the need for relatively long-term commitments by all parties if the collaboration is to be sufficiently stable, make it essential for future European initiatives to be co-ordinated. We therefore recommend that the ABRC should review the whole field of international scientific ventures as a prelude to discussions with comparable bodies throughout Europe on the facilities required by European scientists during the next decade and on ways of providing these most effectively.

TABLE 8.1. EXAMPLE OF POSSIBLE SAVINGS

SAVINGS		1986-87	1987-88	1988-89	1989-90	1990-91	1991-92	1992-93
Domestic	%	5	10	15	20	25	25	25
	£m	1	2	3	4	5	5	5
CERN	%	0	2	5	12	18	25	25
	£m	0	0.7	1.8	4.2	6.3	8.8	8.8
TOTAL	£m	1	2.7	4.8	8.2	11.3	13.8	13.8
Cumulative saving	£m	1	3.7	8.5	16.7	28.0	41.8	55.6

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3. What Attracts Students Towards Physics? Physics Bulletin, 36 169 1985 P I P Kalmus.

4. CERN Past Performance and Future Prospects:
   - I. CERN's Position in the World of High Energy Physics: Research Policy 13 183 1984
   - II. The Scientific Performance of CERN Accelerators: Research Policy 13 247 1984
   - III. CERN and the Future of World High Energy Physics: Research Policy 13 311 1984

   J Irvine and B Martin

5. A Study of Economic Utility from CERN Contracts: CERN 75-5; H Schmied

6. Economic Utility Resulting from CERN Contracts (2nd Study): CERN 84-14; M Bianchi-Streit, N Blackburne, R Budde, H Reitz, B Sagnell, H Schmied and B Schoor

7. Resources Given to High Energy Physics in 1982 in the CERN Member States: Comparison with Previous Censuses: CERN MI-DI/84-126 C Roche

8. Support of Research Grants: Report of a Council Study: (Lewis Report) SERC August 1984

9. A Strategy for the Support of Core Science: Science Board SERC 1984

APPENDIX 1: MEMBERSHIP OF THE HIGH ENERGY PARTICLE PHYSICS REVIEW GROUP

Sir John Kendrew CBE FRS (Chairman)
Professor E A Ash CBE FRS FEng
Professor Sir Douglas Hague CBE
Professor Sir Jack Lewis FRS
Sir John Mason CB FRS
Professor K A Pounds CBE FRS
Sir Francis Tombs CBE FEng

Secretary
K D J Root

Consultant to the Group
Dr C H Llewellyn Smith FRS

APPENDIX 2: THE COMMON CRITERIA

1* Councils and their Boards/Committees/Groups are invited to use the criteria listed here to discuss and compare relative benefits. Whenever practicable, reference should be made to objective data in support of the assessment (eg demographic data, social costs: relevant government expenditure etc.) in relation to the cost of the research.

Scientific Policy Criteria

1. Excellence of study field
   Where benefits are attributable to a high proportion of the research being intrinsically of high intellectual value.

2. Excellence of the research workers
   Where benefits are attributable to the exceptional quality of the individuals or teams to be employed in the activity.

3. Pervasiveness of the activity
   Where benefits include the impetus to advances in other and related fields of science in addition to the primary field.

4. Social and/or economic importance
   Where expected benefits arise from the work being directed to supporting social or economic aims.

5. Significance for the training of scientific manpower
   Where benefits will include training and experience for scientific research workers.

6. Educational importance
   Where benefits will include a contribution to education.

7. Significance in maintaining national scientific prestige
   Where benefits will contribute to national reputation.

* Extract from instructions to Research Councils 1975 Forward Look

Management Criteria

2. A set of selected management criteria are also offered. These apply to the consideration, from a management policy point of view, of alternatives which have already been assessed on the scientific policy criteria.

A. Efficiency of operation
Where improvements in organisation and/or plant would lead to a general increase in efficiency.

B. Obsolescence
Where the maintenance of a capability (at whatever level of activity) requires replacement within the Forward Look period of a major item of obsolescent plant or equipment.

C. Timing
Where a start on a new or increased activity within the Forward Look period is critical if the expected benefits are not to be lost or much reduced.

D. Dependence on Science Budget Support
Where there is likely to be limited support, national or foreign, available for work related to the activity except the Science Budget.

E. Availability of scientific manpower
Where an activity attracts priority by virtue of greater availability of scientific manpower for it (or its execution is constrained by lack of it).

F. Scope and limits of redeployment
Where the priority accorded to an activity is conditioned by difficulties or opportunities of redeployment.

APPENDIX 3: VISITS

CERN

DESY, Hamburg

The Ministry of Research and Technology (BMFT), Federal Republic of Germany

Rutherford Appleton Laboratory

The Physics Departments of the following universities:

- Cambridge
- Durham
- Lancaster
- Liverpool
- Manchester
- Nottingham
- Oxford
- Imperial College of Science and Technology, University of London

APPENDIX 4: LIST OF WITNESSES WHO GAVE ORAL EVIDENCE TO THE GROUP

Professor Sir Michael Atiyah FRS, Mathematical Institute, University of Oxford
Professor I Butterworth CBE FRS, Director of Research, CERN
Professor J I G Cadogan FRS, Chairman, Science Board, SERC
Professor B L Clarkson, CVCP
Professor D C Colley, Chairman of Nuclear Physics Board (SERC)
Professor H Curien, Minister for Science and Technology, France
Dr P Day, Inorganic Chemistry Department, Oxford
Professor J D Dowell, Chairman, Particle Physics Committee
H Fish Esq CBE, Chairman, NERC
Dr H H Haunschild, Staatssekretär, BMFT (The Ministry for Research and Technology), Federal Republic of Germany
Sir James Gowans FRS, Secretary, MRC
J Irvine Esq, Science Policy Research Unit, University of Sussex
Professor T W B Kibble FRS, Chairman, Nuclear Physics Theory Subcommittee, Nuclear Physics Board, SERC
Professor Sir John Kingman FRS, Chairman, SERC
Dr R Klapisch, Director of Research, CERN
Professor L Lederman, Director, Fermilab
Dr G Manning, Director, RAL
B Martin Esq, Science Policy Research Unit, University of Sussex
Professor Sir Alec Merrison FRS, Chairman of CERN Council
Professor E Picasso, Director & LEP Project Leader, CERN
Professor J R Quayle FRS, CVCP
Professor M Rees FRS, Institute of Astronomy, University of Cambridge
Sir Ralph Riley FRS, Secretary, AFRC
Professor A Salam FRS, Department of Physics, Imperial College
Professor H Schopper, Director General, CERN
Professor D W Sciama FRS, Department of Astro Physics, University of Oxford
M Shock Esq, CVCP
Professor V Soergel, Director of DESY
Dr G Stafford FRS
Dr J J Thresher, Associate Director (Nuclear Physics), RAL
Professor W F Vinen FRS, Department of Physics, University of Birmingham
Professor D J Wallace, Department of Physics, University of Edinburgh

Professor V F Weisskopf

Professor J C Willmott CBE, Department of Physics, University of Manchester

Dr H O Wüster, Director, JET

Sir Douglas Wass GCB

Seminar at Imperial College of Science and Technology

Presentations by:

Dr J Carter

Dr R J Cashmore

Dr J Ellis FRS

Dr N Ellis

APPENDIX 5: THOSE SUBMITTING WRITTEN EVIDENCE

Dr J M Ashworth, VC University of Salford

Professor J E Baldwin CBE FRS, The Dyson Perrins Laboratory, University of Oxford

J N Barker Esq

A J Bell Esq, Phoenix Flexible Tubes Ltd

Professor K Berkelman, Cornell University

Dr H Blumenfeld

Professor T L Blundell FRS, Department of Crystallography, Birkbeck College, London

Dr A R Bradwell, Department of Immunology, University of Brimingham

T Branwhite Esq, Trevor Branwhite Trailers Ltd

Dr D Bugg

Professor P N Butcher, Department of Physics, University of Warwick

Sir Clifford Butler FRS, VC Loughborough University of Technology

P M Butler Esq, Morfax Ltd

R W N Chantler Esq, Business Development International

J D Chapman Esq, Marconi Electronic Devices Ltd

Professor J M Charap, Physics Department, Queen Mary College, London

P E Collins Esq, English Electric Valve Co Ltd

P A Cramb Esq, Smith Associates Consulting Systems Engineers

R C Dabski-Nerlich Esq, BICC (Export) Ltd

Dr C J S Damerell, Rutherford Appleton .Laboratory

Dr H E Davies, Computer Unit, University of Exeter

P G Davey Esq, Meta Machines Ltd

Professor P Dunnill, Department of Chemical and Biochemical Engineering, University College, London

Professor E A V Ebsworth FRSE, Royal Society of Chemistry

Professor R J Elliott FRS, Physical Secretary of the Royal Society

Professor P Falk-Vairant, National Institute of Nuclear and Particle Physics, Paris

L E Fisher Esq, L E Pink Engineering Ltd

Dr R G Forbes, Department of Electronic and Electrical Engineering, University of Surrey

The Rev A Ford , Chaplain, St Paul's Girls' School

J Ferguson Esq, Farnell International Instruments Ltd

Professor S L Glashow, Department of Physics, Harvard University

SI Mr V Green

Dr S Geer, CERN

Professor Sir John Gunn FRSE

Dr J Hassard, Wilson Laboratory, Cornell University

Professor F F Heymann, Department of Physics and Astronomy, University College, London

Dr R Hill, Department of Physics, Robert Gordon's Institute of Technology

Professor W Hoogland, NIKHEFF, Amsterdam

Dr C J Humphreys, Department of Metallurgy, University of Oxford

M G Iles Esq, Marconi Quest CAE

Dr D J E Ingram, VC University of Kent

Professor J M Irvine, Department of Theoretical Physics, University of Manchester

Dr T Johnson FRSE, VC Heriot Watt University

D H Jones Esq, Anderman & Ryder Ltd

Professor Sir Ewart Jones FRS

S J Laredo Esq, Pantak Ltd

Dr P M Lee, Physics Department, University of Lancaster

N Leslie Esq

Sir James Lighthill FRS, Provost, University College, London

Dr P J Marcer

Dr D Miller, Department of Physics and Astronomy, University College, London

F E Mitchell Esq, Smith & Johnson (Keithley) Ltd

J Ovens Esq

Professor W G Overend, Master, Birkbeck College, London

Professor W K H Panofsky, Stanford Linear Accelerator Centre

Sir Rudolph Peierls FRS

Professor J Peoples, Chairman, Division of Particles and Fields, American Physical Society

Dr T J Pitt

Dr R W Pringle OBE FRSE

Dr J M Robertson, Edinburgh Microfabrication Facility, University of Edinburgh

Professor J Sacton, Chairman of the European Committee for Future Accelerators

Professor J Sandweiss, Department of Physics, Yale University

F J Smith Esq, Johnson Matthey Chemicals Ltd

F Thompson Esq, Grenson Electronic Ltd

Professor D T Thouless, Department of Physics, University of Cambridge

D R Trowbridge Esq, Chairman, CERN Task Force, British Overseas Trade Board

Professor R Turlay, Department of Elementary Particle Physics, CEN, Saclay

Dr R E Turner, Chairman of Physics, University of Sussex

Professor R A Waldron, School of Mathematics, Ulster Polytechnic

Professor J Walker, Department of Physics, University of Birmingham

Dr J F Wheater, Department of Theoretical Physics, University of Oxford

Professor B H Wiik, DESY, Hamburg

D R Willis Esq, Tesla Engineering Ltd

M N Wilson Esq, Oxford Instruments Ltd

Professor G Wolf, DESY, Hamburg

APPENDIX 6: PAPERS RECEIVED

A. PUBLISHED PAPERS

ABRC

Scientific Opportunities and the Science Budget 1983
Scientific Opportunities and the Science Budget 1984
Further Advice on the Science Budget 1984

Cabinet Office

Annual Review of Government Funded R and D 1984

CERN

Convention for the Establishment of a European Organisation for Nuclear Research - As amended January 1971

Annual Report 1983

Experiments at CERN 1983, 1984

A Study of Economic Utility Resulting from CERN Contracts; H Schmied: CERN 76-5

Economic Utility Resulting from CERN Contracts (Second Study): M Bianchi-Street, N Blackburne, R Buddi, H Reitz, B Sagnell, H Schmied and B Schoor: CERN 84-14

Resources given to High Energy Particle Physics in 1982 in the CERN Member States: Comparison with Previous Censuses: C Roche: CERN MI-DI/84-126

LEP - Introductory Brochure

DESY

HERA - A Super Electron Microscope for Studying the Smallest Building

Blocks of Matter March 1984

SERC

Annual Report 1983-84

Rutherford Appleton Laboratory Annual Report 1983

Support of Research Grants: Report of a Council Study 1984

Biotechnology and British Industry, SERC 1984

Nuclear Structure Physics in the UK, SERC 1983

Particle Physics Committee Annual Report 1982-83, 1983-84

Strategy for the Support of Core Science, Science Board 1984

The Needs of Engineering, Engineering Board 1985

CERN

CERN Past Performance and Future Prospects:

I. CERN's Position in the World of High Energy Physics Research Policy
13 193 1984

II. The Scientific Performance of CERN Acelerators Research Policy
13 247 1984

III. CERN and the Future of World High Energy Physics Research Policy
13 311 1984

J Irvine and B Martin.

B. SPECIALLY CONTRIBUTED PAPERS

AFRC: Submission on opportunity cost of HEPP

CBI : Submission on opportunity cost of HEPP

CVCP: Memorandum 1; concerning HEPP in the undergraduate curriculum and the effect on teaching and research in physics departments of UK withdrawal from particle physics.

Memorandum 2; concerning priorities within the Science budget.

European Physical Society: on UK particle physics research

MRC : Submission on opportunity cost of HEPP

NERC: Submission on opportunity cost of HEPP

Royal Society: on the standing of UK particle physics and the effect of UK withdrawal

SERC: Submission on opportunity cost of HEPP

SERC Particle Physics Committee:

1. Support of Particle Physics at RAL
2. An Overview of Particle Physics and the Role of the UK
3. The Need for Additional Funds in Particle Physics
4. The Need for a Broadly Based HEP Programme
5. Particle Physics and Technological Spin-off
6. Impact of Particle Physics on Education
7. The Overlap of Particle Physics with Other Areas of Science

APPENDIX 7: OUTLINE OF UK CONTRIBUTIONS TO THREE LEP DETECTORS

ALEPH

The Electromagnetic Calorimeter: End Caps - Glasgow and RAL

: Electronics - RAL

Inner Tracking Chamber - Imperial College and RAL

Time Projection Chamber: Calibration - Glasgow

Event Trigger - RAL

DELPHI

Muon Chamber - Oxford

Outer Detector - Liverpool

Data Acquisition - Oxford and RAL

Solenoid - RAL under contract to the whole collaboration

OPAL

The Electromagnetic Calorimeter: End Caps - Cambridge, Queen Mary College and RAL

Forward Detectors - Birkbeck College and University College

Muon Detectors: Cylinder - Manchester

: End Caps - Birmingham

Vertex Detector: Data Capture - Cambridge and QMC

APPENDIX 8: THE ANALYSIS OF DATA FROM THE UA1 EXPERIMENT

UA1 is the largest collaborative experiment so far carried out in High Energy Particle Physics. It is also at the forefront of interest because the high energy (now 630 GeV) of the SPS $p\bar{p}$ collider allows the creation of heavy particles like the W, Z and top quark which are beyond the energy reach of any other accelerator currently available. It is therefore interesting to examine how the data analysis has been carried out, as UA1 is likely to be a prototype of experiments at LEP and HERA, and the part played by the UK groups at Birmingham, QMC and RAL. The final extraction of physics results for publication is, of course, heavily dependent on the foregoing data evaluation.

One reason for the rapid appearance of results from the experiment, which first obtained data in 1981, has been the attention that was given to the preparation of the analysis programs. A larger fraction of the effort went in this direction than had been usual in past experiments. Furthermore, the adoption of a computer independent memory management and editing systems meant that contributions to the program developments could conveniently be made outside CERN. As would be expected, the most interesting results have been obtained on site. This has been made possible by having an on-line data selection called the "express line", which contains, for example, high transverse momentum lepton candidates and therefore the bulk of the most exciting physics. The remaining 90% of the data were processed somewhat later using a variety of off-line selections. A vital ingredient in the evaluation of the data has been the Megatek 3-D graphics facility on which all W, Z and other rare event candidates have been scanned, often within 24 hours of the data taking.

Important contributions have been made by UK physicists both at CERN and in the K. More than half the UK staff involved have spent periods of upwards of one ear in residence at CERN while the rest have commuted fairly heavily, spending eriods typically of 100 days per year at CERN. They have thus been able to ontribute rather effectively to the software development and processing of the ata. Because of the networking arrangements it is not particularly important where the program developments were made. Examples of contributions that have been made to the software by UK physicists are:

a. Basic processing routines for the parts of the apparatus under their responsibility.

b. The program for preparing data summary tapes - on which physics analysis is performed.

c. The bulk of the Megatek programming.

d. Programs to select events on-line and off-line for full processing.

e. Algorithms to select 'jets' of particles.

f. Algorithm to identify electrons.

At CERN much of the day to day responsibility for data processing has been in the hands of UK staff. In terms of physics analysis on site, major contributions have been made to the observation of the W and Z in their muonic decay modes, the top quark study and the analysis of "missing energy" events which appear to represent a new type of phenomenon (supersymmetry?). The analysis of 'jet' events in terms of QCD has largely been a UK affair.

In the UK a Megatek has been operational at Birmingham since the start of the experiment and one at RAL for the last two years. These have been used both for program development and physics analysis. At Birmingham the earliest piece of physics done entirely outside CERN was completed in 1982, on multiplicity distributions. In 1983/4 events containing di-muons below the Z-mass were analysed also leading to a publication. The algorithm to identify electrons, used in the top-quark search, was prepared entirely at RAL with the help of the Megatek. About a quarter of the entire data processed so far has been done in the UK. Only one other piece of physics analysis (the observation of charmed particles in jets) has been carried out exclusively off-site (in the USA) but it is anticipated that much more will be done this way in the future. QMC hope to acquire a Megatek to attach to their VAX 11/750 computer. Meanwhile they are able to make use of the RAL Megatek. Original scanning of W and Z events for data taken in 1984 has been done at Birmingham and missing energy events are being examined at RAL.

In summary, it has proved possible for UK physicists, whether resident at CERN or in the UK, to make a large impact on the UA1 data analysis. Major contributions have been made to the software and data processing. Specific physics topics have been studied outside CERN. In recognition of this UK speakers have frequently been selected to report at international conferences

Professor J Dowell
Chairman of the Particle Physics Committee

APPENDIX 9: COMMENTS ON THE MAIN FEATURES OF THE DETECTORS FOR LEP

The electron-positron collider, LEP, now under construction at CERN, is expected to become operational in 1989. It will become CERN's major accelerator facility and will be the research base for more than 1000 particle physicists. Four out of the six detector system originally proposed for use at LEP have been approved by CERN. In approving these four detectors (codenamed OPAL, ALEPH, DELPHI and L3) it was hoped that they would between them cover adequately the wide variety of physics that is expected to emerge, while at the same time providing some degree of overlap in the physics coverage with significantly different detection techniques. Some of the more important features of the detectors are mentioned briefly below.

The OPAL detector is a general purpose system based firmly on already proven techniques. It is intended to be a safe design which can be built, commissioned and brought into operation quickly. This includes the coil for producing the magnetic field which use conventional water cooled copper conductor.

The ALEPH detector incorporates a superconducting coil to produce the required magnetic field. The design aims at achieving fine granularity and good pattern recognition throughout so that many very closely spaced tracks can be clearly identified within narrow cones or jets of particles. The ability to pick up individual electrons within these jets is another important feature.

DELPHI is perhaps the most complex and innovative detector at LEP. It has a powerful system of specially developed Cherenkov counters which make it by far the best detector at LEP for identifying hadrons. In addition it contains some of the important features of the ALEPH design including a super-conducting coil to provide the magnetic field. Because of its complexity DELPHI may well require a lengthy period of commissioning before all aspects of the detector are fully operational.

The L3 detector is perhaps the most specialised of the four LEP detectors, concentrating particularly on identifying and measuring with good energy resolution both electrons and muons. The volume of magnetic field required for the latter is considerably larger than any of the LEP detectors.

About half of the UK community will be working at LEP, with groups involved in three out of the four approved experiments viz OPAL, ALEPH and DELPHI. This should enable UK physicists to participate in a well balanced programme of research and to play a prominent role in producing much of the new physics that is expected to emerge from this powerful new electron-positron collider.

Dr J J Thresher
RAL

APPENDIX 10: HIGHLIGHTS OF HIGH ENERGY PHYSICS AT CERN

The following summary of CERN's many achievements concentrates on highlights, of which the most fundamental and far-reaching concern nucleon (proton and neutron) structure and the strong force, and the nature of the weak force.

1) Hadron Spectroscopy

Experiments at the PS on the spectrum and properties of strongly interacting particles (hadrons) played an important role in establishing the quark model. They discovered and studied:

a) many mesonic (quark-antiquark) particles, most notably members of the family of particles which includes the A2 and K^* (1420) mesons;

b) many baryonic (three quark) particles, most notably those formed in KN interactions and the Ξ^* states.

The UA1 experiment at the proton-antiproton collider has produced the first evidence for the sixth (top) quark.

2) Hadron Cross-Sections

Experiments at the PS, ISR and SPS and the $p\bar{p}$ collider have studied many reactions which throw light on the size, transparency and nature of hadrons. Important results include:

a) measurements of elastic and inelastic pp, $p\bar{p}$ and πp cross-sections, especially the demonstration at the ISR that the pp cross-section rises with energy and the study of the reaction $\pi^- p \rightarrow \pi^0 n$ at the PS which helped establish the Regge model of such reactions;

b) the first systematic study of Σp and Ξp cross-sections at the SPS;

c) the demonstration by ISR experiment that there is a "central plateau" in the momentum distribution of secondary particles produced in inelastic collisions and that this distribution scales with energy.

3) Nucleon Structure and the Study of the Strong Force at Short Distances

Of many important results, the following were fundamental:

a) demonstration by the Gargamelle neutrino experiment at the PS that neutrinos interact with point-like constituents in nucleons which have the properties postulated for quarks and that nucleons contain neutral constituents (gluons);

b) first quantitative evidence for Quantum Chromodynamics (QCD), the theory of the strong force, from bubble chamber and electronic neutrino experiments at the SPS;

c) further evidence for QCD and discovery that quarks behave differently in nuclei and nucleons (EMC effect) in muon experiments at the SPS;

d) demonstration that quarks respond to the strong force as point-like particles at the ISR;

e) direct evidence for QCD including the first direct evidence for gluon-gluon interactions from the proton-antiproton collider.

4) Electromagnetic Interactions

Although proton accelerators are not best suited to a direct study of electromagnetic interactions, CERN has made significant contributions to this field, e.g. a direct measurement of the lifetime of the neutral pi-meson, which provides evidence for the colour degree of freedom of quarks, and studies using secondary beams of photons. One fundamental contribution was the high precision measurement of the magnetic moment of the muon, which provided a very stringent test of quantum electrodynamics and was of great importance in establishing faith in the underlying principles used to construct the unified electroweak theory and QCD, and also allowed a direct and elegant test of relativity.

5) Weak Interactions

CERN's major contributions, several of which were absolutely fundamental, include:

a) discovery of the decay $\pi \rightarrow e\nu$ and study of the decay $\pi^+ \rightarrow \pi^0 e^+ \nu$ at the SC, which were vital in unravelling the characteristics of the weak force;

b) precision studies of the violation of the symmetry between matter and antimatter in neutral K meson decays;

c) precision studies of the weak decays of strange particles, especially in the hyperon beam at the SPS, and of charmed particles;

d) the discovery of neutral currents, a new form of the weak force, in the Gargamelle experiment at the PS which provided the first vital hint of electroweak unification;

e) the discovery of the W and Z at the SPS collider which established the unified electroweak theory.

6) Technology

CERN's major achievements include: invention of the "horn" used to make focussed neutrino beams, development of wire (Charpak) chambers for detecting particles, construction of the first proton-proton storage ring (with the best vacuum, 10-12 torr, achieved over a large volume), first use of superconducting magnets in an accelerator, development of a source of antiprotons and invention of the stochastic cooling technique which made the proton-antiproton collider possible.

7) Theory

The numerous important contributions to almost every aspect of theoretical particle physics which originated at CERN include the following: construction of the multiperipheral model of hadron collisions, Cabibbo's theory of weak decays of hadrons, the discovery and development of supersymmetry and supergravity, the discovery of the so-called triangle anomaly and Bell's invention of a test of locality in quantum mechanics.

C H L S

APPENDIX 3

DOE/ER-0233

Report of the 1985 High Energy Physics Advisory Panel Study

# of the

U.S. High Energy Physics Program 1985 - 1995

September 1985

U.S. Department of Energy
Office of Energy Research
Division of High Energy Physics
Washington, D.C. 20545

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October 15, 1985

Dr. Alvin W. Trivelpiece
Director, Office of Energy Research
U.S. Department of Energy
1000 Independence Avenue SE
Washington, DC 20585

Dear Al:

I am writing to transmit the "Report of the 1985 HEPAP Study of the U.S. High Energy Physics Program 1985-1995". The report was discussed at the HEPAP meeting on July 1-2, 1985.

The HEPAP study which took place June 2-8, 1985 was preceded by a major information gathering activity during the sping of 1985. The study was held so that HEPAP would make an in-depth review of the U.S. high energy physics program, focussing on the next ten years. The usual 1 1/2 to 2 day meetings do not permit in-depth study of the issues and in formulating its advice, HEPAP must necessarily draw upon its "capital" of background and knowledge. A principal motivation for the study was thus the desire to build up that capital.

The next decade is a period in which the U.S. high energy physics program faces both great opportunities and great challenges. The completion of the Fermilab TEVATRON and the Stanford Linear Collider will present outstanding opportunities for the program for the late 1980's and beyond. The effective utilization of these new facilities is an essential requirement. Similarly, major new opportunities will exist for U.S. scientists as well as their international counterparts in programs at LEP, HERA, and TRISTAN which will become operational around 1990. Important as all of these will be, they do not reach a sufficiently high collision energy to explore properly the TeV mass range where on the basis of rather general and powerful arguments, fundamentally new phenomena will be revealed. As you know, this has been the basis of the SSC project. Accordingly, a substantial part of the study was devoted to a reevaluation of the SSC goal and to an analysis of the transition to the "SSC era".

To summarize, the panel concluded that in 1985, the arguments for the SSC are even stronger than they were in 1983 and the SSC remains the program's highest priority. Furthermore, the U.S. program is sufficiently strong in intellectual resources and scientific manpower to maintain a vital and creative physics research effort during the transition to the SSC. Not surprisingly, however, the funds for SSC R and D, construction, initial detector equipment and pre-operating would have to be largely incremental. The non-SSC program would, of course, be reduced as the SSC neared completion. The panel has estimated, from today's perspective, that the non-SSC level of effort could decrease, relative to the FY85 level by about 30% by the end of the transition period. The panel also found, again from today's perspective, that after the start up of the SSC a healthy program could be mounted at a level of effort about 10% above the FY85 level.

The study also evaluated the current and near term state of the U.S. high energy physics program. The scope and diversity of that program are important elements in its vitality and its ability to make fundamental discoveries. Within the context of such a broadly based program, the panel identified a subset of programs which it felt should proceed with priority.

Finally, it is a pleasure to acknowledge the important contributions of the many participants in the study. Their knowledge, and their patience and generosity in working with the panel were essential ingredients for the successful completion of the study.

Sincerely,

Jack Sandweiss

Jack Sandweiss
Chairman, High Energy Physics
Advisory Panel

JS/ks

EXECUTIVE SUMMARY

Motivated by the need to gain a better understanding of the U.S. high energy physics program, including a reassessment of the goal of building the Superconducting Super Collider (SSC), the High Energy Physics Advisory Panel (HEPAP) has carried out an in-depth study of the U.S. High Energy Physics Program. The HEPAP Study, which covered all aspects of the U.S. program, was held June 2-8, 1985, at the Coolfont Conference Center in Berkeley Springs, West Virginia. In preparation for the Study, a major information-gathering activity was carried out during the spring of 1985.

The Panel has concluded that the physics justification for a multi-TeV, high-luminosity hadron-hadron collider is even stronger today than it was in 1983 at the time of the original HEPAP recommendation. Furthermore, the technical successes achieved in the SSC research and development program reinforce the confidence that this facility can be built within the costs and on the time scale estimated in the Reference Designs Study.

The Panel has evaluated the physics opportunities in the program for the period of approximately 10 years before the SSC would come into operation. These opportunities provide for a rich physics program with excellent prospects for fundamental discoveries. The superconducting Tevatron at the Fermi National Accelerator Laboratory (Fermilab) is operating at an energy of 800 GeV and provides the highest energy fixed-target facility in the world. The Fermilab Collider will become operational in 1987 and will be the world's highest energy hadron collider, extending the energy range to 1.8 TeV from 0.6 TeV available now at the CERN $S\bar{p}pS$. The Stanford Linear Collider (SLC), which will come into operation in 1987 at the Stanford Linear Accelerator Center (SLAC), will be the first e^+e^- collider to reach the energy of the Z^0 and also represents a pioneering effort toward a new class of electron-positron colliders. The effective utilization of these new facilities is an essential requirement.

The physics opportunities also include major U.S. participation in research programs at new facilities abroad: at CERN, the Large Electron-Positron (LEP) project will become operational in 1989, providing e^+e^- collisions initially in the Z^0 range and later at higher energies, up to 200 GeV in the center-of-mass; in Japan, the TRISTAN project will become operational in 1987, providing e^+e^- collisions up to a center-of-mass energy of about 60 GeV. In West Germany, the Hadron Elektron Ring Anlage (HERA) project which is expected to begin operations in 1990, will provide $e^{\pm}p$ collisions up to center-of-mass energy above 300 GeV, opening new opportunities for research.

The Panel has identified a limited number of programs which, because of their intrinsic importance, their likely impact on the course of future research, and their key role in the U.S. program, should proceed with priority. The Panel places the following major programs in this category: The Collider Detector Facility (CDF) and D0 projects at Tevatron I, the L3 program at LEP, the Mark II and Stanford Linear Detector (SLD) projects at the SLC, and the CESR program at Cornell. The Panel also considers the smaller scale efforts involving studies of CP violation with kaons, high sensitivity studies of rare kaon decays, and certain parts of the non-accelerator program to be in this category.

It is clear that a project of the magnitude of the SSC will require major redirection of high energy physics resources during the next 10 years. However, this Study shows that it will be possible to achieve a reasonable transition into the SSC program. Some of the existing programs will be terminating just as extensive effort on SSC detectors will need to commence. The timely completion of the SSC will provide a truly forefront facility for the world's high energy physics community. The Panel notes, however, the inevitable deterioration of the U.S. program and the difficulty of maintaining continuity of the field if the SSC were delayed appreciably beyond the presently anticipated time scale. If this were the case, there would be no frontier facility in high energy physics in the U.S. in the mid-1990s.

Finally, the Panel notes the importance of maintaining and strengthening the technology research in advanced accelerator R&D. This research is essential to the long-term progress of the field.

On the basis of this Study, HEPAP makes the following recommendations:

1. We recommend that the SSC R&D be given highest priority in the U.S. High Energy Physics Program so that the project can proceed to an early construction start and rapid completion. In particular, for FY 1986, we support the requested incremental allocation of $7 million to SSC R&D, primarily so that early substantial industrial involvement in the magnet R&D effort can be initiated.

2. We recommend that the limited category of forefront programs identified in the report proceed with priority.

3. We recommend that the overall funding be adequate to permit the effective implementation of the broadly-based program providing essential diversity and scope with high priority to the special programs, and to pursue the crucial SSC R&D effort.

   Comment: For FY 1987 this would require a small increase beyond the FY 1985 total level of effort. With reduced construction activity, this would allow the increased funding required for the utilization of the new capabilities coming into operation (the SLC at SLAC and the Tevatron at Fermilab) and for the SSC R&D effort.

   It is clear that construction of SSC and fabrication of detectors for SSC will require incremental funding above this level. A funding profile such as shown in Section IV would ensure the scientific vitality and stature of U.S. high energy physics during the period prior to SSC operation. After the SSC is completed, it appears that an excellent program, including the SSC and a reduced non-SSC program, could be supported at a funding level about 10 percent above the current (FY 1985) level of effort.

4. We recommend that advanced accelerator R&D be strongly supported. A continued and strengthened effort in this area is essential to the long term progress of the field.

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SECTION I

Introduction

Two years have passed since the High Energy Physics Advisory Panel (HEPAP) recommended the immediate initiation of a high-luminosity proton-proton collider project with center-of-mass energy between 20 and 40 TeV. In that time, as will be noted in Section II, much has happened. The project has been better defined, and significant progress has been made on the necessary research and development and design. Because of major and widespread activity in high energy physics, much more is now understood about the exciting prospects and technical challenges that will be presented by the use of the Superconducting Super Collider (SSC), as the project has come to be known.

During this period, new data, both scientific and operational, have come from the world's highest energy collider, the CERN SpṗS operating with a center-of-mass energy of about 0.6 TeV, as well as from facilities with lower interaction energies.

The present HEPAP Study was motivated by the desire to examine the U.S. program in depth, to reassess the SSC goal in light of the scientific and technical developments of the last two years, and to understand how this project would affect and interact with the U.S. high energy physics program in the period before it will become operational. The present HEPAP Study was also motivated in large part by the desire to give HEPAP an opportunity to gain an understanding of the U.S. program in greater detail and depth than is possible at the normal 1-to-2 day meetings. The process has been very useful, and HEPAP will be better able to make evaluations and recommendations in the coming year.

The strength and vitality of the U.S. program during the next ten years is of particular concern since the SSC will not begin physics experiments until 1995. Each of the U.S. facilities now existing or under construction will then be in a mature phase of its research program, or in some cases at the end of its useful life. Substantial shifts of high energy physics manpower will be necessary in advance of SSC operation in order to prepare for experiments and to support the accelerator research and development and construction efforts. As discussed in Section IV, manpower shifts will occur naturally as the programs at the current facilities mature.

High energy physics facilities are of such size and cost that it is not, in general, practical to duplicate major facilities. Thus, if scientists are to be able to work on the broad range of forefront facilities, the international cooperation which has been traditional in high energy physics will be even more important. Facilities abroad are, and will be, important aspects of the U.S. program and have received substantial attention during the Study.

Focused on major experimental programs and facilities, this report complements a recent DOE review of its university programs (see "Report of the Technical Assessment Committee on University Programs" DOE/ER-0182, October 1983). A second topic not treated herein is the important role of data processing and computers in detector design, experimental analyses, accelerator physics, and theoretical computation and simulation. Continued advances in this area are critical to progress in high energy physics. This topic has been the subject of intensive studies by the HEPAP Subpanel on Computer Needs for the Next Decade and the HEPAP Subpanel on Theoretical Computing. The reader is referred to those reports for further discussion (see DOE ER-0234 and DOE ER-0205).

The HEPAP Study took place June 2-8, 1985, at the Coolfont Conference Center in Berkeley Springs, West Virginia. It was preceded by a major information-gathering activity during the spring of 1985. Working Groups of HEPAP organized informal information-gathering sessions covering the major aspects of the program, which were held at the three large accelerator laboratories--Stanford Linear Accelerator Center (SLAC), Fermi National Accelerator Laboratory (Fermilab), and Brookhaven National Laboratory (BNL). As part of each of the laboratory meetings, a "town meeting" was held which provided an opportunity for an informal exchange of views between interested physicists and HEPAP members. Another gathering was held at the National Academy of Sciences in Washington, DC, with the directors (or their representatives) of the domestic and foreign high energy physics laboratories. At that time, the future plans for each of the laboratories were presented and discussed.

The Study was also brought to the attention of the high energy physics community by a description published in the American Physical Society's Division of Particles and Fields Newsletter, in which the views of the community were solicited and the schedule of information-gathering meetings and town meetings was given. Appendix A lists the Participants in the Study, the Working Groups, and the presentations given at the information meetings.

SECTION II

The Superconducting Super Collider (SSC)

A. Historical Survey

The intellectual beginning of the Superconducting Super Collider (SSC) concept can be traced back to the 1982 Summer Study at Snowmass, Colorado, organized by the Division of Particles and Fields of the American Physical Society. During the three years since that Study significant progress has been made, as a result of which the high energy physics community is ready to embark on preparation of the Conceptual Design Report for that facility. The major events in the evolution of the SSC concept are enumerated below.

Summer 1982: A Summer Study of the American Physical Society's Division of Particles and Fields was held at Snowmass, Colorado. The topic of the study was "Elementary Particle Physics and Future Facilities." An in-depth examination of the idea of a multi-TeV/beam proton-proton collider resulted from this meeting. Strong, widespread support for the physics goals of such a facility emerged.

February 1983: A week-long workshop was held at the Lawrence Berkeley Laboratory (LBL) in California to consider detector problems for a high energy, high-luminosity hadron-hadron collider.

March 1983: A 1-week workshop was held at Cornell University in Ithaca, New York, to consider technical and cost questions associated with construction of a 20 TeV/beam hadron-hadron collider.

July 1983: A Subpanel of the High Energy Physics Advisory Panel (HEPAP), convened early in 1983 to consider the future high energy facilities in the U.S., recommended construction of a 10-20 TeV/beam, high-luminosity, hadron collider. This recommendation, unanimously endorsed by HEPAP as highest priority for high energy physics, was transmitted to the Department of Energy (DOE).

Fall 1983: DOE initiated preliminary R&D for the SSC. Hearings were held before the House Science and Technology Committee concerning redirecting resources toward the SSC R&D.

December 1983: The Reference Designs Study was chartered by the Directors of the U.S. high energy accelerator laboratories with the energy and luminosity goals defined.

March 1984: DOE assigned responsibility for oversight of the national SSC effort during the R&D and preconstruction phase to the Universities Research Association.

Spring 1984: The Reference Designs Study was held at LBL with about 150 participants. It was concluded that a 20 TeV on 20 TeV proton-proton collider is technically feasible. The Study, which also contained construction cost estimates and schedules, was extensively reviewed by DOE personnel and their consultants.

June-July 1984: A second DPF Summer Study was held at Snowmass, Colorado, on the design and utilization of the Superconducting Super Collider. The physics questions that could be studied with a multi-TeV, high-luminosity, hadron-hadron collider were examined in considerable detail, and agreements for such an instrument were considerably sharpened. In addition, detector issues have been examined in depth leading to the conclusion that, with the existing techniques, deteccors can be constructed capable of exploiting the high energy and high-luminosity proposed. Preliminary cost estimates of several 4-pi detectors have been obtained and desirable detector R&D identified.

Summer 1984: Initiation of the Phase I R&D program for the SSC was approved by the Secretary of Energy. Extensive work on model magnets for the SSC was already under way at Brookhaven National Laboratory (BNL), Fermi National Accelerator Laboratory (Fermilab), Lawrence Berkeley Laboratory (LBL), and the Texas Accelerator Center (TAC).

Fall 1984: The Central Design Group (CDG) was formed, headquartered at the Lawrence Berkeley Laboratory. The CDG was charged with directing and coordinating all of the SSC R&D work nationwide.

April 1985: An SSC Siting Parameters Document was submitted to the Department of Energy.

B. Physics Developments

Two years have now passed since the original HEPAP recommendation on the SSC. Thus, one should examine physics developments since that time to see whether there have been any significant changes in our understanding of the physical world to warrant any modifications of the original recommendation. The core of the argument for the SSC was the belief that the Standard Model (the unified electroweak theory, plus QCD), even though remarkably successful in providing an elegant description of all known phenomena, cannot be the final answer. The Standard Model does not explain many key features such as particle masses and requires many ad hoc parameters. Furthermore, on the basis of both the general arguments and specific models, it was believed that the capability to explore mass scales in the TeV region is necessary to provide significant new clues about the nature of a more comprehensive theory.

The last two years have strengthened appreciably the confidence in the Standard Model. More abundant samples of W and Z bosons from the CERN $p\bar{p}$ Collider have allowed one to conclude with much higher precision that the masses of W and Z bosons and their decay modes are in conformity with the

Standard Model. Simultaneously, the improved accuracy of the neutrino electron scattering experiments and of the e^+e^- annihilation experiments has provided improved values of the weak mixing angle parameter which is in agreement with the value derived from the W mass. In addition, the study of jets at the high energy collider machines confirms in a semi-quantitative way the predictions of perturbative QCD.

Evidence for deviations from the Standard Model has been looked for in various areas. Experiments looking for neutrino oscillations, supersymmetric particles, and rare muon decay modes are some examples of such searches. No significant deviations from the Standard Model have been found.

Finally, the mysterious Higgs particle still has not been found in spite of additional searches. This spinless particle (or family of particles) arising out of the Higgs mechanism is postulated to explain the symmetry breaking in the electroweak theory, and its discovery is one way to resolve the difficulties which would otherwise arise in the Standard Model. The model, however, gives no detailed predictions as to its mass, except the general requirement that the mass cannot be much in excess of 1 TeV. Alternatively, if Higgs particle(s) do not exist with mass below about 1 TeV, the electroweak interactions would have to become strong in the 1 TeV constituent center-of-mass range, leading to a wealth of new phenomena. Thus, the ability to probe the TeV mass region still appears to be required if this all-important question is to be solved.

The case for the SSC can be reinforced by citing several other important recent physics developments. The hints of unexplainable mono-jet events from CERN may be harbingers of new physics. But the difficulties of studying these questions at the CERN machine appear formidable. Higher energy machines will be needed to resolve this question.

The very important negative result from the proton decay search performed by the Irvine-Michigan-Brookhaven (IMB) group appears to rule out the simplest Grand Unification scheme, the minimal SU_5 model. This particular solution predicted a desert (i.e. absence) of new phenomena over a very wide energy range (up to 10^{15} GeV). The fact that a different solution seems to be required if grand unification is to be realized reinforces the belief that a wealth of new phenomena may be expected in the TeV range.

Finally, the trend which began several years ago regarding the interplay of many ideas in physics and cosmology has been growing stronger. The cosmological arguments for investigating higher energies are quite powerful. One is even more confident today than two years ago that SSC will shed significant new light on the early evolution of our universe.

To summarize, there are compelling arguments why the TeV mass range is expected to yield important new physics. Among these arguments is the comprehensive success of the Standard Model up to masses of 0.1 TeV, together with its failure to address such fundamental questions as the true nature of spontaneous symmetry breaking, the origin of mass patterns, the equality of lepton and hadron charges, and the possible unification of quarks and leptons. Reaching the TeV mass range in the center-of-mass system of the interacting elementary constituents is still the most important goal for U.S. high energy physics.

C. Progress in Superconducting Accelerator Technology

The Fermilab Tevatron, the first high energy superconducting accelerator, achieved first beam just before the HEPAP meeting of July 1983. Since that time, the machine has operated routinely at 800 GeV and several physics experiments have been completed.

The remarkable success of this sophisticated magnet technology applied on such a large scale gives us confidence that the SSC will represent a relatively straightforward engineering extension of the Tevatron experience. The Tevatron has demonstrated that one can operate 1,000 large superconducting magnets over long periods of time, that an appropriate helium cryogenics plant can be made to work, and that this whole combination can provide a productive physics tool. To achieve the SSC, development work with the view of minimizing costs, increasing reliability, and decreasing heat leaks is necessary. The proof of principle, however, for the SSC has been established with the successful operation of the Tevatron.

Very promising technological developments have taken place with respect to superconducting strand and cable. The Fermilab accelerator is constructed with a superconducting NbTi strand capable of carrying 1800 A/mm^2. At the time of the Reference Designs Study, it was projected that strand capable of carrying 2400 A/mm^2 would be available at the time of SSC construction. Recently, thanks to extensive university, laboratory, and industry efforts, superconducting strand capable of carrying 2600 A/mm^2 has become available commercially in production quantities.

In addition, there have been encouraging results in the efforts to reduce the diameter of the superconducting filaments. This is particularly useful for the high field magnets. Since the unwanted sextupole component at injection decreases significantly as one reduces filament size below that presently used, a large amount of work has been done to produce finer filaments. The recent results indicate that filaments can be made fine enough so that sextupole corrections can be made by means of lumped (rather than distributed) coils, thus generating significant cost savings for the high field magnets.

D. The Central Design Group and SSC R&D Activities in FY 1985

In the summer of 1984, Universities Research Association, the contractor chosen by DOE to carry out the SSC Phase I program, upon recommendation of its SSC Board of Overseers, created the SSC Central Design Group (CDG) and appointed Professor Maury Tigner as Director. By September 1984 it had been decided to locate the CDG at the Lawrence Berkeley Laboratory, and on October 1, 1984, the CDG research and development activities officially began. The funding available for SSC R&D in FY 1985 is $20 million.

The major objectives for FY 1985 are to:

1. Set up the Central Design Group.
2. Carry out a variety of magnet and cryostat R&D aimed at providing the technical information necessary to make a choice of basic magnet type by the end of the fiscal year.
3. Develop a Siting Parameters Document on the information needed to make an accurate evaluation of any proposed site.
4. Study a number of accelerator physics and systems issues that impact on the choice of basic magnet type (aperture, commissioning and operations, low temperature operation, photodesorption, etc.)
5. Assist in the development of superconducting strand of improved current-carrying capacity (discussed in Section C above).

In carrying out the program, the CDG, whose staff at LBL presently consists of 25 physicists and engineers plus 10 support personnel, has relied on the capacities of 4 magnet R&D centers, on industry, and on universities and laboratories. In addition to the work carried out in these various places, there has been a major involvement of many members of the high energy physics community through workshops, panels, and task forces conducted by the CDG in order to get advice and expertise on many issues. The magnitude of this involvement can be gauged by the list of workshops, panels, and task forces which is given in Table II-1. All of the activities have occurred in FY 1985. Some have completed their work; most are ongoing.

The CDG is responsible for the coordination and management of the SSC R&D effort nationwide. Tasks executed by the CDG staff in FY 1985 concentrated on the accelerator physics and accelerator systems research (objective 4 above). There have also been significant contributions in those areas by personnel from universities and national laboratories. The focus has been on the specification of the magnet aperture in the linear and nonlinear regimes, as well as on single-beam and beam-beam instabilities. An aperture report is due by the end of July as input to the process of selecting the basic magnet type in September 1985.

TABLE II-1

Workshops, Panels, and Task Forces Conducted by SSC/CDG During FY 1985

Accelerator Physics:

1. Aperture Workshop and Task Forces
2. Impedance Task Force
3. Clustered IR Study Group
4. "Realistic" Lattice Workshop

Accelerator Systems:

1. Task Force on Commissioning and Operation of the SSC
2. Photodesorption Task Force
3. Photodesorption Experiment
4. Power Supply and Quench Protection Task Force
5. Task Force on Low Temperature Operation of the SSC

Conventional Systems:

1. Site Parameters Document Review Panel
2. Tunneling Technology Review Panel

Magnets:

1. DOE Workshop on Fine Filament NbTi Strand
2. Magnet System Test Site Task Force
3. Fiscal and Management Review Panel
4. Technical Magnet Review Panel (Interim)
5. Technical Magnet Review Panel (New)
6. Magnet Type Selection Advisory Panel

Project Planning And Management:

1. Cost Estimating Task Force

General CDG Administrative:

1. Business Affairs and Management Advisory Panel

Detectors:

1. Task Force on Detector R&D for the SSC

The accelerator systems work has focused on questions of commissioning and operating an SSC constructed with any of the various magnet types currently under consideration, of quench protection and power supply systems for these different machines, and of special vacuum requirements caused by photodesorption from the wall of the beam pipe by the synchrotron radiation emitted by 20 TeV protons. An experiment is presently under way at the vacuum ultraviolet light source at Brookhaven National Laboratory. Data on a warm bore tube have already been obtained and preparations are under way to perform an experiment in the summer of 1985 on a tube at liquid helium temperature.

Another important direct activity of the CDG staff has been the development of site criteria and the preparation of a Siting Parameters Document. The recent submission of this technical advisory to the DOE was a major milestone of the Phase I program.

The bulk of the SSC R&D funds in FY 1985 have been spent at the four magnet R&D centers: Brookhaven National Laboratory (BNL), Fermi National Accelerator Laboratory (Fermilab), Lawrence Berkeley Laboratory (LBL), and the Texas Accelerator Center (TAC). The superconducting magnet program is aimed at making the necessary technical development and demonstrations of several different basic magnet types. These can be roughly described by a two-by-two matrix of parameters--low field or high field, and one beam channel or two beam channels per cryostat.

The lower field (approximately 3 Tesla) magnet is an iron-dominated design, called superferric, and is being pursued by TAC in a version with two channels per cryostat. TAC has made a number of short models (1-m in length) and one 8-m model. TAC has a contract with industry to produce one 28-m model in FY 1985 and two more in FY 1986 in order to demonstrate the capability of manufacturing long magnet units.

The high field (approximately 6 Tesla) magnet is a conductor-dominated design, sometimes called "cosine theta." It has been developed in versions with both two channels per cryostat and one channel per cryostat, and with iron close to the coils and also with non-magnetic collars holding the conductor firmly in place. A number of 1-m models with two channels per cryostat and one channel per cryostat have been made. Most recently, Fermilab, BNL, and LBL have been collaborating on a design that builds on the experience obtained from previously constructed model magnets. In this collaboration, LBL is responsible for conductor and cable development and fabrication of 1-m models, while BNL is focusing mainly on larger magnet fabrication and on magnet measurements. Fermilab is working on cryostats and lower cost production technologies. Recently, the first 4.5-m model of this new design has been fabricated and measured.

The current R&D program has accomplished important goals. It has established that magnets of small bore can be fabricated and operated successfully, with performance equal to or better than "short sample" specifications with little or no "training." Field quality is good. By the end of the fiscal year, over 80 meters of beam channel of both low and high field magnet types will have been manufactured and tested. This is an impressive achievement!

Equally important have been the developments in cryostat techniques. The heat leak that results mainly from the need to support the heavy cryopackage (at liquid helium temperature) from the outside (at room temperature) must be kept within reasonable bounds or the needed refrigeration capacity will be excessive. Calculations done during the Reference Designs Study indicated that an acceptably low heat leak could be achieved if appropriate thermal shielding and thermally efficient mechanical supports were incorporated into the design. Measurements at Fermilab on a 12-m cryostat model incorporating these improvements have shown a combined 10^0 K and 4^0 K heat leak of less than 0.25 watts/meter of beam channel. At this level, the SSC refrigerator heat load would be acceptable. Continued work is expected to yield further improvements.

In the last quarter of FY 1985, the data on all the magnet types, including cost estimates made independently by the laboratories and the CDG and by two separate engineering groups in industry, are being assembled as input to the basic magnet type selection. This activity is scheduled to take place in phases during July and August 1985, resulting in a recommendation by the Magnet Type Selection Advisory Panel and a selection by the CDG in September 1985. Several panels and task forces will spell out the status of the magnet program in all its aspects and identify areas for further R&D leading to design and construction of prototype SSC magnets in FY 1986.

E. SSC R&D Program in FY 1986 and Beyond

The chief FY 1986 objectives are to:

1. Design prototype SSC magnets based on the selected basic magnet type, develop the necessary tooling, and begin fabrication of prototypes, with the goal of producing enough magnets to begin a systems test in early FY 1987.

2. Examine again the conventional construction items, including tunnels, exits, safety measures, and experimental halls.

3. Prepare a cost-optimized design of the technical and conventional systems and a non-site-specific conceptual design report with cost and schedule estimates.

4. Contract with several industrial firms to manufacture prototypes of short dipole or quadrupole magnets and make an engineering design based on these prototypes.

5. Examine detector R&D needs.

The current President's Budget Request for the SSC R&D in FY 1986 is $20 million. At this budget level, the CDG will only be able to work on the most essential aspects. It expects to be able to carry out the technical demonstrations necessary for a credible conceptual design report, but will be forced to restrict its magnet R&D efforts to dipoles alone and initiate only minimal industrial involvement.

The CDG's budget appeal, submitted to DOE in April 1985, asked for $27 million for the SSC. The added $7 million is divided into $2 million for additional tooling at the magnet R&D centers for quadrupoles and correction coil packages, and $5 million for the contracts with industry. The latter are especially important in order to achieve early participation by industry and the development of the technical "know-how" aimed at large-scale manufacture of these sophisticated magnet-cryogenic units. Participation by several industrial firms is important in order to develop the capabilities of a number of contractors so that ultimate costs can be kept within bounds.

The CDG budget request for FY 1987 consists of $55 million in operations for the SSC, and $5 million for necessary capital equipment, mostly for instrumentation of the systems test. The budget reflects the need for a major effort on fabrication of prototype magnets of all types, partly at the magnet R&D centers and partly by industry, for the systems and lifetime tests, accelerator systems reliability simulations, as well as for work on conventional systems.

A recent Task Force on Detector R&D for the SSC has recommended early commencement of a serious R&D effort on detectors capable of exploiting the luminosity and energy of the SSC at turn-on. Some preliminary work was done at the 1984 Snowmass Summer Study. It is envisioned that in FY 1986 there would be a modest effort of study groups and workshops on pattern recognition, calorimeter parameters, custom integrated circuit development, triggering and data acquisition, and also the drawing together and coordination of the Monte Carlo simulation codes. These efforts would require funding at the level of

$500,000-$750,000. By FY 1987, significant R&D activity would commence in all of these areas, as well as in the area of radiation damage to components. The Task Force recommended funding levels for this detector R&D of $4-5 million in FY 1987 and $6-8 million in FY 1988.

F. SSC Overview

The physics reasons behind the recommendation of the 1983 HEPAP Subpanel on New Facilities for a multi-TeV, high-luminosity hadron collider as the needed instrument to reach and explore the TeV mass range have been strengthened in the intervening 2 years.

A number of technical achievements in different areas have validated the assumptions of the Reference Designs Study (RDS) and have even shown promise of leading to further cost savings. Among these developments are:

1. Improved performance of NbTi superconducting filaments, with current-carrying capacities of commercially available high-homogeneity strands now beyond that posited in the RDS.
2. Successful construction of small-bore magnet models in a variety of lengths and beam channel configurations, magnets that meet or surpass "short sample" expectations and have good field quality.
3. Design and construction of magnet support systems for cryostats that have effective heat leaks of 0.25 watts/meter in rough agreement with the Reference Designs Study specifications.

To these specific technical achievements can be added the advances made in defining the magnet aperture, in studying the different magnet types for ease of commissioning and ease and cost of operating, in preparing site criteria, and in addressing a host of other topics.

The SSC Central Design Group and the magnet R&D centers have been remarkably successful in achieving so much in less than a year. The major accomplishments just cited show that there is promise of cost reductions in the future. There are many reasons why the momentum of the R&D program must not only be maintained but increased in the coming year. It is particularly important to get early and significant industrial involvement in the magnet R&D program. The additional $7 million requested for FY 1986 is essential for this purpose. Every effort should be made to obtain increased funding to provide it; but it should be allocated, even if it comes at the expense of the rest of the high energy physics program. The SSC R&D must proceed with the highest priority.

SECTION III

Research Opportunities in the Next Ten Years

There are exciting opportunities for research in the next ten year period provided by both the existing facilities and by those about to come into operation. In particular, two new forefront facilities, the Tevatron and the SLC, will come into operation early in this period. For ease of reference in the main part of this Section, a list of high energy physics facilities currently available or under construction in the U.S. and abroad is given in Appendix B.

The research programs which could be carried out in the next ten years with these facilities are rich in potential for fundamental discovery, broad in scope, and form a complex, often interconnected pattern. Since research by definition involves the study of the unknown, it is difficult to evaluate research programs in advance. Experience has shown that many factors, some not always understood in advance, affect the productivity of a research effort. Unexpected results or unexpected connections, sometimes of great importance, can and do occur. It is primarily for these reasons that a healthy research program must be a broad program. It is essential for the U.S. high energy physics program to continue to be a diverse effort with strong activities in each of the major avenues of the field.

Within this pattern, however, it is possible to identify a limited category of experiments or programs which enter a new experimental regime in such a way as to have clear promise for new fundamental discoveries. Because of their intrinsic importance, because of the likely impact their results would have on the course of future research, and because of their importance to the U.S. program, it is viewed as essential that such forefront efforts proceed in a timely fashion. This category includes the following major programs: the CDF and D0 projects at Tevatron I, the L3 program at LEP, the Mark II and

SLD projects at the SLC, and the CESR program at Cornell. The Panel also considers the smaller scale efforts involving studies of CP violation with kaons, high sensitivity studies of rare kaon decays, and certain parts of the non-accelerator program to be in this category.

In the following, descriptions and brief comments are given on the research opportunities which will be available to U.S. high energy physicists in the interim period.

A. Proton-Antiproton Colliders

The proton-antiproton ($\bar{p}p$) colliders have an excellent potential for the discovery of new phenomena because of the very high energies of the hadron constituents. In the past there was a concern that evidence for new physical processes could not be extracted from the background of hard constituent scattering. The discovery of the W and Z at the S$\bar{p}$pS Collider established that certain decay channels of the W and Z can be easily observed in high energy hadron collisions. Thus, for example, it is feasible to consider the detection of states which can be produced in hadron collisions and which subsequently decay into W's and Z's. Should there be additional vector bosons which decay into leptons with an appreciable branching ratio, they are likely to be discovered at the Tevatron if their masses are less than 700 GeV (assuming a luminosity upgrade as discussed below). It is also possible that the two-jet decay of such heavy bosons will emerge from the background if the energy resolution of detectors continues to improve. It is likely that top quark decays will be observed in large numbers at the S$\bar{p}$pS, after the UA-1 and UA-2 detectors have been upgraded, and also at the Tevatron. It may be possible to detect still heavier quarks at the Tevatron.

The signatures of the theoretical models which seek to explain the dynamics of the Higgs mechanism typically point to the existence of particles with masses in the range of hundreds of GeV to several TeV. The decays of some of these particles involve W's, Z's, and heavy quarks. Whereas the entire range will be within the domain of the SSC, the lower end of this range will be accessible to the S$\bar{p}$pS and the Tevatron.

A relative comparison of the discovery potential of the S$\bar{p}$pS and the Tevatron can be made by comparing the production of the standard electroweak bosons, more massive gauge bosons (V), and heavy quarks (Q) in a run of 10^7 effective seconds. The results are given in Table III-1 which considers planned luminosity improvement programs at both Colliders.

TABLE III-1

Comparison of the S$\bar{p}$pS and Tevatron Colliders*

	S$\bar{p}$pS (upgraded/1988)	Tevatron I (1987)	Tevatron I (upgraded/1989)
Center-of-Mass Energy (GeV)	630	1800	2000
Peak Luminosity ($cm^{-2}sec^{-1}$)	3×10^{30}	10^{30}	10^{31}
Events of $W^{\pm} \rightarrow e^{\pm}\nu$	1.0×10^4	1.2×10^4	1.4×10^5
Events of $Z^0 \rightarrow {}^+e^-$	3.6×10^2	9.0×10^2	1.1×10^4
Number of t and $\bar{t}$ (40 GeV/c)	6.0×10^4	1.8×10^5	2.2×10^6
Mass Limits for Heavy V (GeV/c^2)**	240	500	700
Mass Limits for Heavy Q (GeV/c^2)**	90	130	220

* The yields assume a run of 10^7 seconds at peak luminosity.

**The limits are based on the production of 100 produced particles in a run of 10^7 seconds at peak luminosity.

Because there will be copious production of W's and Z's, it will be possible to make critical tests of the Standard Model which depend on precision measurements of their properties. One such example is the ratio of the masses of the W and Z.

The S$\bar{p}p$S Collider has been in operation since late 1981. The commissioning of the Tevatron Collider at Fermilab has just begun, and Fermilab expects to achieve first colliding beams in a test run in September 1985.

The first use of the Tevatron for colliding beam experiments is scheduled for 1987. The parameters of the Center for European Nuclear Research (CERN) and Fermilab Colliders, together with their detectors, are as follows.

1. The S$\bar{p}p$S Collider

The S$\bar{p}p$S normally operates at a center-of-mass energy of 630 GeV. A peak luminosity of 4 x 10^{29} cm^{-2} sec^{-1} was achieved in 1984, and the integrated luminosity accumulated since 1981 is 0.6 pb^{-1}. Throughout this period, two major detectors, UA-1 and UA-2, took data. While both detectors were able to detect W's and Z's successfully, this experience led the experimenters to initiate upgrades of the detectors' capabilities.

CERN has also initiated a luminosity improvement program which has the objective of increasing the peak luminosity by a factor of 10. CERN expects to reach a peak luminosity of 3 x 10^{30} cm^{-2} sec^{-1} by 1987. Moreover, they expect to accumulate an integrated luminosity of 10 pb^{-1} during 1988.

The UA-1 detector is being upgraded by improving the calorimeter energy resolution, by adding a high resolution vertex detector, and by xtending the muon detection system to a larger solid angle. In ddition to these detector improvements, the data acquisition system ill be upgraded to match the increase in luminosity. The muon etection system improvements will be completed in 1985, and the emainder of the improvements will be completed in 1987. These mprovements will lead to better energy resolution for electrons, muons, and jets and will, thus, enhance the detector's ability to determine the transverse energy carried away by particles which do not interact in the detector, such as neutrinos. With 23 U.S.-supported physicists among the 178 UA-1 collaborators, this detector represents a significant effort for the U.S. as well as for Europe. However, the priority and pace of this detector are set by the European program.

The UA-2 detector will be upgraded by extending the hadron calorimeter coverage from 40° to 5° with respect to the beam axis. This will be accomplished by replacing the toroidal magnets with calorimeters, thereby making the detector a totally non-magnetic detector. Other changes will be made to improve the electron identification and tracking in the central calorimeter.

2. The Tevatron Collider

The Tevatron Collider is designed to have a luminosity of 10^{30} cm^{-2} sec^{-1} and to operate at the peak energy of the Tevatron. It is presently operated at 800 GeV in the fixed-target mode. It is anticipated that it can be operated at 900 GeV per beam as a collider. After two test runs, one in September 1985 and another in fall 1986, Collider operations are to begin for experimental physics. At that time, the center-of-mass energy and the peak luminosity are expected to be 1800 GeV and 10^{30} cm^{-2} sec^{-1}, respectively. In order to exploit the ultimate capability of the Tevatron and its potential for discovery as illustrated by Table III-1, Fermilab intends to increase gradually both the energy and luminosity. In particular, Fermilab plans to initiate an improvement program in 1987 which will increase the luminosity to $10^{31}cm^{-2}$ sec^{-1} by 1989.

Two major detectors are planned for the Tevatron Collider: CDF and D0. The CDF detector is currently being fabricated. The D0 detector is in the prototype testing stage, and fabrication will begin in FY 1986.

The CDF detector employs a large solenoidal magnet which contains track chambers surrounding the beam pipe. The superconducting solenoid magnet is enclosed within a lead-scintillator electromagnetic calorimeter which, in turn, is enclosed in an iron-scintillator hadron calorimeter. The calorimeters utilize a highly segmented tower geometry in order to define the energy and direction of a jet. It will be possible to detect electrons and hadrons emerging from the interaction point at an angle of 1° or greater. Muon detection is provided over part of the solid angle. The construction of the detector in its current scope will be complete in late 1986. The partially completed detector will be placed in the Tevatron Collider during the September 1985 beam test, and it will be used again in the 1986 colliding beams test.

The CDF group is planning an upgrade of its detector in order to extend the muon coverage and to improve the electron identification. They also plan to add a high resolution vertex detector in order to have the capability of identifying heavy quarks. Finally, they plan to upgrade the trigger system. They have requested funds in FY 1987, 1988, and 1989 for these purposes.

Unlike CDF, the D0 detector has no central magnetic field, but emphasizes optimum muon and electron identification and minimizes missing transverse energy resolution. Its designers have chosen highly segmented uranium-liquid argon calorimetry, utilizing projective geometry. The calorimeters will measure the energy of particles which emerge from the interaction point at angles greater than 1° with respect to the beam axis. A special effort is being made to reduce both the statistical errors and the systematic errors in the measurement of electron and hadron energies. Electron identification is achieved through measuring shower development in the calorimeter and the ionization deposited in a transition radiation detector. The detector also has a magnetized iron muon detector covering nearly

4-pi steradians. On the basis of the plan presented to HEPAP, the detector can be completed in 1990, with a staged turn-on beginning in 1989.

It is worth noting that the opportunities to explore the physics of 2 TeV proton-antiproton collisions are not limited exclusively to the large detectors. Several small experiments are planned to run at the Tevatron I Collider concurrently with the large detectors. In general, these experiments are designed to search for very specific phenomena.

The CDF and D0 detectors have an excellent capability to detect new phenomena, such as massive gauge bosons and heavy quarks. Given their complementary nature and physics potential, high priority should be given to both the CDF and D0 detectors in order to assure their timely completion.

Because new phenomena may not conform to our current expectations, it is natural to expect the configurations of these detectors to evolve in response to our growing understanding of the physical processes which take place at these energies. A program of detector upgrades and accelerator improvements will be an essential part of the hadron collider physics program.

B. Electron-Proton Collider

Scheduled to begin physics experiments in mid-1990 at the Deutsches Elektronen-Synchrotron (DESY), HERA will extend electron-proton and positron-proton collisions to a new energy range (E_{cm} = 314 GeV). It will be the first $e^{\pm}p$ colliding beam accelerator and, incidentally, the first national accelerator facility involving significant international participation in its construction. Its design luminosity of $2.5 \times 10^{31} cm^{-2} sec^{-1}$ should allow the determination of the proton structure functions in a substantially new range of momentum transfers, $2000\ (GeV/c)^2 < Q^2 < 10000\ (GeV/c)^2$, far beyond anything achievable anywhere else in the world. (The maximum Q^2 achievable in deeply inelastic muon or neutrino scattering at the Tevatron II is about 400 $(GeV/c)^2$.) These experiments, together with observations of the final state, will allow new tests of the Standard Model, especially of perturbative QCD. In addition, the structure functions have practical applications, diminishing uncertainties in the predictions for hadron collisions in the SSC energy range.

The electron and positron beams are expected to be transversely polarized, and DESY has plans to enable rotation of the polarization, to provide longitudinally polarized electrons and positrons, an extremely useful capability.

With regard to now unpredictable new phenomena, one can anticipate on general grounds that many potentially new kinds of forces or particles to which HERA may be sensitive would also be detectable in e^+e^- annihilations at SLC or LEP or in $\bar{p}p$ collisions, such as at S$\bar{p}$pS or Tevatron I. However, data obtained at HERA would frequently provide information complementary to data obtained elsewhere. In addition, HERA will have special sensitivities to certain effects, such as excited electron states or new electron-quark interactions.

Clearly, HERA offers unique opportunities for experimentation at the world's first ep colliding facility, and groups of U.S. physicists have already expressed an interest in participating in the experimental program. It is desirable to have U.S. experimenters involved in the HERA program and, for this purpose, a modest commitment of capital equipment funds would be appropriate.

C. Electron-Positron Colliders

Over the past decade, experiments studying electron-positron annihilation have made enormous contributions to elementary particle physics. The power of this technique is due to the extreme simplicity and well-understood nature of the initial state and the ability of an electron and positron to annihilate into pure gauge fields. New fundamental particles can be produced copiously with backgrounds at low levels unobtainable by any other techniques.

The U.S. program in electron-positron colliders has been, and will continue to be, in the forefront of this area of particle physics. In addition, U.S. physicists are actively participating in the major foreign e^+e^- facilities.

The following discusses the physics opportunities at e^+e^- colliders in order of decreasing center-of-mass energy.

1. Large Electron-Positron Project (LEP)

The Large Electron-Positron Project (LEP) storage ring, with a circumference of 27 km, is being constructed at CERN in Geneva, Switzerland. LEP is scheduled for initial operation for physics in 1989 and is expected to achieve its design luminosity of 1-to-2 x 10^{31} cm^{-2} sec^{-1} fairly quickly. Initially, it will study the physics of the Z^0 resonance. The small beam energy spread of LEP would allow studies of narrow resonances such as toponium. Subsequently, LEP will be upgraded to the center-of-mass energy of approximately 200 GeV by the addition of superconducting rf cavities. LEP is the only planned e^+e^- collider searching in this higher energy range for new phenomena. The 200 GeV LEP will permit searches for new types of leptons and quarks up to masses of 100 GeV. It will also permit study of the production of Z^0Z^0 pairs, W^+W^- pairs, and searches for heavier vector bosons and other particles. LEP will also be able to search for Higgs particles up to a mass of 70 GeV. These experiments will address some of the most fundamental questions with respect to our understanding of electroweak processes, including the origin of symmetry breaking and the origin of masses.

There are four detectors planned for LEP (ALEPH, DELPHI, OPAL, and L3). The construction of the LEP collider and its detectors represents a major commitment of the European physics community. There are nearly 1,000 physicists working on the ALEPH, DELPHI, OPAL, and L3 detectors, and there is U.S. participation in all four of them. Their properties, as well as those of the SLC detectors, are summarized in Table III-2.

ALEPH, DELPHI, and OPAL are 4-pi detectors, each with strong magnetic fields. Each of these detectors has its distinct particle identification device to measure hadrons as well as electrons and muons. ALEPH has a very large volume time projection chamber for high resolution tracking and particle identification and a highly segmented tower-geometry calorimeter. DELPHI uses a smaller time projection chamber for tracking and uses ring-imaging Cherenkov detectors for particle identification. A novel high-density projection chamber is used for electromagnetic calorimetry. OPAL has a 160-layer drift chamber which operates at 4 atmospheres pressure. This provides excellent ionization information and high resolution tracking. Lead glass is used for electromagnetic calorimetry. The funding for these detectors comes predominately from non-U.S. sources.

The L3 detector has a magnetic volume of 12m x 12m x 12m and a field of 0.5 Telsa. Inside the magnet are high precision muon chambers with a resolution of 30 microns and 4-pi uranium hadron calorimeters with a resolution of $0.5/\sqrt{E}+0.1$. There are 12,000 bismuth germanate (BGO) crystals which measure the coordinate of electrons and photons to ±3mm

TABLE III-2
Summary of the New e^+e^- Detectors

	ALEPH (LEP)	DELPHI (LEP)	L3 (LEP)	OPAL (LEP)	Mark II (SLC)	SLD (SLC)
Vertex Detector	chamber + μ-strips	chamber + μ-strips	TEC	chamber	chamber + possible μ-strips or CCD's	CCD's
Tracking Device	TPC 1 atm r = 1.8 m n = 300	TPC 1 atm r = 1.2 m + outer	—	DC 4 atm r = 1.6 m n = 160	DC 1 atm r = 1.5 m n = 72	DC 1 atm r = 1.0 m n = 80
Coil	s.c. 1.5 T	s.c. 1.2 T	warm 0.5 T	warm 0.4 T	warm 0.5 T	warm 0.6 T
Tracking Resolution	0.13% p	0.15% p	0.03% p μ only	0.15% p	0.12% p	0.13% p
Particle Id	dE/dx 4.5% σ	dE/dx + RICH	—	dE/dx 3.5% σ	dE/dx 7% σ	RICH
EM calor.	Pb-gas	HDPC	BGO	Pb glass	Pb-LA	U-LA
EM resolution	$18\%/\sqrt{E}$	$18-20\%/\sqrt{E}$	1%	$6.5\%/\sqrt{E}$	$12\%/\sqrt{E}$	$8\%/\sqrt{E}$
Hadron cal. Resolution	$100\%/\sqrt{E}$	$100\%/\sqrt{E}$	$50\%/\sqrt{E}$ + 10%	$100\%/\sqrt{E}$	—	$45\%/\sqrt{E}$
Muon Det.	full	full	high res	full	55%	full

Key:
TEC — Time Expansion Chamber
CCD — Charged Coupled Device
TPC — Time Projection Chamber
DC — Drift Chamber
RICH — Ring Imaging Cherenkov Detector
HDPC — High Density Projection Chamber
LA — Liquid Argon
(p in GeV)

and there is a vertex chamber with a resolution of 30 microns. L3 is is designed to be complementary to other e^+e^- detectors, providing a momentum resolution of 1 percent for photons, electrons, and muons. The resolution of electrons, muons, and photons will enable L3 to identify the production of rare particles such as massive Higgs and supersymmetric particles. The large magnetic volume of L3 permits it to adapt easily for possible future plans of LEP.

The L3 detector is under U.S. leadership. There are 400 scientists working on this detector with major collaboration from the U.S. The resources for this detector come about equally from the U.S., the Soviet Union, and the Western European countries, with important contributions from the People's Republic of China.

The LEP program, with its four detectors, is expected to produce important new fundamental physics results. Because of the major U.S. participation and leadership in the L3 experiment and its key role in the U.S. high energy physics program, it should have high priority for its planned completion.

2. SLAC Linear Collider (SLC)

The SLAC Linear Collider (SLC) is designed to produce e^+e^- collisions at 100 GeV center-of-mass energy. It will begin initial operation for physics in 1987. In addition to being a pilot project to develop the technology of producing and colliding micron-sized electron and positron beams, it will be the first electron-positron collider to study the formation and decay of the Z^0 boson. The physics of this region includes precise measurements and tests of the electroweak interaction, determination of the number of neutrinos, searches for new particles, studies of the top quark (if its mass is less than half the Z^0 mass), and high data rates for QCD and heavy quark studies.

The SLC has a design luminosity of 6×10^{30} cm^{-2} sec^{-1}. Since the SLC is a novel collider, it is expected that the design luminosity will be approached more slowly than it would be for a conventional storage ring. Nevertheless, once design luminosity is achieved, about 2 million Z^0 decays per year are expected to be observed at the SLC, approximately the same number as are expected to be observed per year at LEP per detector. If, as planned, LEP begins running primarily at energies above the Z^0 around 1992, the SLC will be the only e^+e^- collider exclusively studying Z^0 decay.

The SLC has two technical advantages over storage rings. First, detectors can be placed closer to the interaction region than in a storage ring. This allows the position of secondary vertices to be measured with high accuracy, improving the measurement accuracy of short lifetimes and increasing the efficiency for tagging heavy quark decays. The second advantage is the ability to produce longitudinally polarized electron beams. This allows the Z^0's to be produced with a tuneable polarization, aiding in the measurement of electroweak interaction parameters and the determination of new particle properties. The ability to produce a polarized electron beam and to measure its polarization will probably not be available until 1989.

The SLC has only one interaction region. The first detector will be an upgraded version of the Mark II detector, which will have been tested on PEP during the 1985 - 1986 run.

The Mark II upgrade includes a new 72-layer drift chamber, which provides high-resolution charged particle tracking and the capability of measuring dE/dx to assist in electron identification. A high resolution inner drift chamber is being constructed for vertex detection, and a silicon microstrip or CCD detector may be added. New end cap calorimeters extend the coverage of electromagnetic calorimetry to the full solid angle.

The scheduled completion of the SLC and the Mark II, as well as the utilization of the SLC, should be given high priority.

The SLD is now under construction by a broadly based collaboration including SLAC, a large number of U.S. university groups and non-U.S. institutions. The present construction schedule allows initial operation of the SLD in 1989. The design of SLD, the second detector for the SLC, has been optimized for the Z^0 energy region. Its main features are: (a) calorimetry over the full 4-pi solid angle with finely segmented tower geometry with good electromagnetic and hadronic energy resolution; (b) particle identification over the full 4-pi solid angle using Cherenkov ring imaging detectors which provide good separation between electrons, pions, kaons, and protons over most of the relevant energy range; (c) a CCD vertex detector starting at 10-to-15 mm from the interaction point with 5-to-10 micron spatial resolution; and (d) uniform technology for all detection systems over the full 4-pi solid angle.

This detector is important to the U.S. program in that it allows the full exploitation of the physics potential of the SLC and should compete favorably with the LEP detectors, as can be seen from the comparisons of Table III-2. This project should be given high priority and the planned completion of the SLD detector should proceed without delay.

3. TRISTAN

The TRISTAN storage ring is under construction at KEK in Japan and is scheduled for completion in 1986. It will be capable of reaching center-of-mass energies up to around 60 GeV. TRISTAN covers an energy range not covered by any other existing or planned e^+e^- collider and thus provides an important new opportunity to discover and study any new phenomena whose thresholds lie in this range. Its physics program will probably stress electroweak interference effects, jet formation and fragmentation, and studies of the toponium system if $t\bar{t}$ bound states are within its energy range.

There are three major detectors at TRISTAN; two of them, TOPAZ and VENUS, are general purpose detectors. VENUS uses a drift chamber in a solenoidal magnetic field for charged particle tracking and a lead glass array for photon detection. TOPAZ also features lead glass but uses a TPC for charged particle identification and tracking. Both detectors are being constructed by Japanese collaborations. The third detector, AMY, is a compact detector emphasizing lepton and photon detection. To this end, the detector uses a high magnetic field, high resolution tracking chambers, and photon counters before the magnet coil. This detector has major U.S. collaboration and leadership.

4. PETRA

The PETRA storage ring at Hamburg, Germany, has taken data on e^+e^- collisions since 1978. It has reached the center-of-mass energy of 47.6 GeV. There has been major U.S. participation in PETRA experiments. The results from PETRA have provided a better understanding of QCD, electroweak effects, and mass limits of new particles. However, in order to concentrate on the HERA construction, the PETRA experimental program will be terminated by the end of 1986.

5. PEP

The PEP storage ring at SLAC has taken data primarily at 29 GeV center-of-mass energy since completion in 1980. PEP is currently the highest energy e^+e^- collider facility in the U.S., and it has obtained a peak luminosity of approximately 3×10^{31} cm^{-2} sec^{-1}. The main PEP detectors

(ASP, DELCO, HRS, MAC, Mark II, and TPC) have made major contributions to the studies of heavy quark fragmentation and lifetimes, the properties of tau decay, jet formation and fragmentation, two-photon physics, and electroweak interference phenomena.

The PEP program will have accumulated about 300 pb^{-1} integrated luminosity by the end of FY 1985. Significant advances cannot be accomplished in a reasonable running time without an increase in the PEP luminosity. A mini-beta upgrade is planned for 1986-87 which will increase the luminosity by a factor of 3 to 5. The main detector which is expected to operate from 1987 on is the TPC detector. With the anticipated addition of a high resolution vertex detector, the TPC detector combines excellent momentum resolution, high-resolution dE/dx capability for electron, pion, kaon, and proton identification, and good electron and muon identification over the full 4-pi solid angle. These features of the TPC detector, together with the projected high luminosity of PEP, will enable it to conduct high sensitivity studies of heavy quark physics, hadronic fragmentation physics, and two-photon physics. The upgrade itself is estimated to cost about $2 million. In addition, the operation of PEP and the TPC detector requires significant resources.

6. CESR

The CESR storage ring at Cornell University has been studying the upsilon resonances and the b-quark systems for the past five years with great success. The luminosity of CESR has increased each year reaching the present value of 4×10^{31} cm^{-2} sec^{-1}. A planned micro-beta upgrade and injection improvement in 1986 are expected to increase the luminosity by another factor of 2 to 3.

Both the CUSB and CLEO detectors are in the process of having major upgrades. The CUSB detector is having an array of BGO crystals installed which will provide the photon resolution needed for measuring the radiative transitions from the narrow upsilon resonances to other bb-bound states. The experimental program of the CUSB detector is expected to last until the completion of the CLEO upgrade.

The CLEO detector is undergoing a phased upgrade which will be completed in 1988. The upgraded detector will have a high resolution drift chamber and a vertex detector for charged-particle tracking, an array of cesium iodide crystals for high resolution photon detection, and improved muon and time-of-flight measurements. This combination will allow a substantial increase in the efficiency for reconstructing exclusive B-meson decays. This ability will significantly advance the study of b-quark decays.

The CESR accelerator and CLEO upgrade will provide a unique facility for the study of the b-quark system. It should proceed with high priority in a timely manner.

7. DORIS

The DORIS storage ring at DESY in Hamburg, Germany, also has been engaged in studying the upsilon resonance region. Both of its detectors, ARGUS and the Crystal Ball, have U.S. participation, with major U.S. participation in the latter. No major accelerator or detector upgrades are planned for DORIS; however, the current program should be competitive with CESR for several years.

8. SPEAR

The SPEAR storage ring at SLAC will be the only e^+e^- collider operating in the charmonium region (3 to 5 GeV center-of-mass energy) until the beginning of operation of the high luminosity Beijing e^+e^- storage ring (BEPC). Although this region has been studied with enormous success for more than a decade, a large number of detailed measurements of J/Psi, Psi', D, F, and Λ_c decays remain to be performed. High luminosity is needed for these investigations, and a mini-beta luminosity upgrade has been installed during the past year. It is expected to increase the luminosity by a factor of 3 to 5 within the next two years.

The Mark III detector at SPEAR was specifically designed to study the low-multiplicity, low-energy states of this region with high efficiency and resolution. A new vertex chamber that is being added to the detector will improve the charged-particle resolution.

The SPEAR program provides unique information on charmed-quark systems in a particularly cost-effective way. If the expected increase in luminosity is achieved, this program should yield important results for at least the next five years.

Fixed-Target Experiments

periments involving particle beams striking stationary targets complement ose with colliding beams because of the large variety of incident and rget particles, the achievable interaction rates, and the broad range of ecialized detectors which can be employed. At Fermilab, the Tevatron II gram of external beam lines which take advantage of the highest available mary proton energy, as well as of the excellent duty cycle delivered by Tevatron, is nearing completion; some of the first round of Tevatron ed-target experiments have begun to collect data, and this program is ected to be fully under way within the next one-to-two years. There has n a resurgence of interest in fixed-target experiments at the AGS. The ition of the capability to accelerate heavy ions, which is presently er way, will provide new opportunities which are of particular interest to the nuclear physics community. The fixed-target program at SLAC has been reduced to the level of about one experiment per year, in addition to test beam activity.

Because of its diversity and the large number of experiments, the fixed-target program as a whole does not lend itself to a single assessment of its priority; but, the experiments can be grouped in terms of the physics questions which they address. This approach has been adopted in the following discussion.

1. CP Violation in Kaon Decays

It is important to refine further our understanding of CP non-conservation in the kaon system as long as significant advances are possible. Recently there have been efforts at BNL looking for CP violation in $K \rightarrow \pi\mu\nu$ and in $K \rightarrow 2\pi$ and at Fermilab in $K \rightarrow 2\pi$. Currently an experiment at Fermilab with a sensitivity to ϵ'/ϵ in the range of 10^{-3} could have a significant impact on the understanding of the Standard Model. Another Fermilab experiment should have the sensitivity to observe CP violation in $K \rightarrow 3\pi$ for the first time. New initiatives, such as a measurement sensitive to a value of ϵ'/ϵ of a few times 10^{-4} or a measurement of the phase difference between η_{+-} and η_{00} to a precision of about 1°, would make important additional advances in this area. Such experiments might be performed at Fermilab or BNL and should have high priority.

2. Rare Kaon Decays

A number of decay modes of the kaon are either forbidden or highly suppressed in the Standard Model. The search for such modes is a sensitive probe of new phenomena. For instance, an observed branching ratio of 10^{-11} for $K \to \mu e$ would be evidence for the existence of a new particle with mass of the order of 100 TeV, and would signal an entirely new force since this decay mode is forbidden by electroweak and strong forces.

An active program at the Brookhaven AGS is investigating a number of channels. The decays $K \to \mu\pi e$ and $K \to \mu e$ are forbidden in the Standard Model by conservation of lepton number but allowed in a number of its theoretical extensions. The experimenters hope to lower the present limits (of order 10^{-8}) by at least three decades.

The mode $K \to \pi\nu\bar{\nu}$ is allowed in the Standard Model only in second order at a rate of a few times 10^{-11}. New generations or other phenomena could significantly increase this branching ratio. The currently approved experiment could lower the present limit (10^{-7}) to near 10^{-10}.

Both the decay $K^0 \to \pi^0 ee$ and the muon polarization in $K^0 \to \mu\mu$ are suppressed by our current model of CP violation; $K^0 \to e^+e^-$ is suppressed by the GIM mechanism and helicity; these too are being studied at the AGS.

The preceding examples illustrate the richness of this field, and it is recommended that the current program be pursued with high priority.

3. Heavy Quark Physics

There has been a broad program of fixed-target experiments at CERN and at Fermilab concentrating upon the detection of heavy quarks produced in hadron, photon, and neutrino-induced reactions. A second generation of these experiments is getting under way at the Tevatron where the increase in the production cross section with energy may make it possible to detect hundreds of decays of hadrons containing b quarks and tens of thousands of those containing c quarks. These experiments will run at an instantaneous interaction rate of around 10^4/sec. However, with the powerful on-line processors and sophisticated vertex detectors which are under development, there is reason to believe that the considerable challenge of triggering and recognizing secondary vertices at significantly greater luminosities can be met. This program holds the promise of detailed studies of heavy quark production, dynamics, spectroscopy, lifetimes, and decay modes as well as ultimately of possible mixing and CP non-conservation. Such knowledge and the necessary technology will be important as well to experimentation at the SSC.

This program should be pursued in a vigorous manner. Planning for major new initiatives should incorporate at least the initial experience from this generation of experiments.

4. AGS Booster

Brookhaven has proposed to add a 1 GeV booster accelerator to the AGS which would enhance its capabilities in several ways: the proton intensity would be increased by a factor of 5, thus making it possible to produce more intense secondary beams, e.g. kaons; the intensity of polarized proton beams accelerated in the AGS would be increased by a factor of about 20; the highest mass heavy ion which could be accelerated in the AGS would be increased from sulphur to gold, as needed for the Relativistic Heavy Ion Collider (RHIC).

There is also a large number of physicists outside of the high energy physics community who are actively interested in physics requiring high proton intensities in the AGS energy range.

Proposals for new accelerators have been made both at Los Alamos (LAMPF II) and Vancouver (TRIUMF II) in order to explore the same physics with even higher average currents (35 μA and 100 μA, respectively) compared with 8 μA at Brookhaven with the Booster upgraded to operate at 2.5 GeV.

The estimated cost of the Booster is approximately $26 million. Construction would begin in FY 1987 and would be completed in FY 1989.

The addition of the Booster represents an attractive enhancement of the AGS which would benefit both the high energy physics and nuclear physics programs at Brookhaven.

5. Tests of Perturbative QCD

The spectacular jet phenomena observed by the UA-1 and UA-2 groups at the CERN Sp̄pS have established that hadronic processes at large momentum transfer arise from the hard scattering of constituents. At the present level of study, the energy and transverse momentum dependencies of inclusive jet yields at collider energies are in accord with expectations of the parton model, supplemented by QCD radiative corrections. Moreover, the angular distributions in the jet-jet center-of-mass systems are in qualitative agreement with predictions. The program of fixed-target experiments at the Fermilab Tevatron includes unique QCD studies which complement those being carried out at the colliders. By studying different scattering subprocesses and exploring a greater range of the relevant scaling variables, they are designed to add to our understanding of QCD phenomenology. Deep inelastic muon and neutrino scattering experiments will determine the structure functions of a variety of nuclear targets, will extend the Q^2 range, and will study jets. The production of prompt photons at large transverse momentum is sensitive to gluon structure functions which are difficult to determine otherwise. The production of chi states (even charge conjugation states of charmonium) and photoproduction will explore novel constituent production mechanisms. Measurements of single hadron inclusive cross sections near the kinematic limit provide new information on jet fragmentation.

In addition, there are some experiments at lower energies which are relevant to perturbative QCD. Examples are the measurement of the ratio of longitudinal to transverse structure functions at SLAC and studies of exclusive interactions at high transverse momenta at BNL.

Tests of perturbative QCD represent an important component of the fixed-target program particularly as the energy domain of the Tevatron will provide data on constituent dynamics which should be relatively free from higher order and higher twist contributions.

6. Hadron Dynamics Other Than Perturbative QCD

A broad class of experiments addresses strong interaction effects not amenable to a perturbative treatment. Although this class properly includes multiparticle production at small transverse momenta and energy dependence of total cross sections, the following concentrates on low energy hadronic properties as studied in the fixed-target program.

Particle spectroscopy has long been a mainstay of experimental particle physics. This area has assumed new importance with the widespread acceptance of the underlying Yang-Mills theory of quarks and gluons. Theoretical techniques are not yet sufficiently developed to make many precise predictions, but one consequence is the existence of "glueballs", quarkless bound states of gluonic fields. Lattice calculations point to a rich glueball spectrum in the 1-2 GeV range, with the lightest states perhaps below 1 GeV. Unfortunately, present calculations are rather ambiguous as to predicted decay width and mixing with pure quark states. In addition to these states, theorists predict with varying degrees of rigor states with exotic numbers of quarks and states consisting of both quarks and gluonic excitations. Interesting candidates for such states have been found in J/psi decays at SPEAR and in hadronic interactions at BNL. Searches for such states are a part of the program at all the laboratories and further proposals are anticipated.

The surprising persistence of spin effects at high energies has led to requests for polarized proton beams of increasing energy. Protons from a polarized ion source have been accelerated to 16.5 GeV in the AGS and extracted. The intensity is 10^{10} protons/pulse and the polarization is 40 percent. As presently configured, the AGS should be able to produce polarized protons up to 22 GeV at an intensity of 2×10^{10} protons/pulse and a polarization of 50 percent. The proposed Booster should raise the intensity by a factor of about 20. An external polarized proton (antiproton) beam derived from Λ^0 ($\overline{\Lambda}^0$) decay is being built at Fermilab. It will have a momentum of up to 200 GeV/c and provide $1\text{-}2 \times 10^7$ protons/pulse at a polarization of 50 percent. Among other parameters, these polarized beam experiments will measure polarized cross section differences in $\bar{p}p$ elastic scattering and investigate spin effects in inclusive production processes.

The proposed measurement of the Ω^- magnetic moment would complete the program carried out at Fermilab over the past several years to determine this parameter for all of the "stable" hyperons.

Taken together as a class, these experiments provide studies of non-perturbative strong interaction phenomena at a more refined level than presently can be reliably predicted from first principles. With the continuing development of lattice and other techniques, these experiments present exciting challenges to theoretical physics.

7. Neutrino Oscillation Experiments

A number of searches for evidence of flavor changes in neutrino beams have been carried out during the past several years at BNL, CERN, Fermilab, and Los Alamos, as well as at several reactors. Such changes would require both non-conservation of individual lepton numbers and non-zero masses for neutrinos. To date, none of these experiments has detected a clear, non-vanishing effect. Instead, each experiment has established upper limits on the mixing between two neutrino flavors and the mass difference between them.

The discovery of flavor-changing leptonic currents or of non-zero neutrino masses would certainly be of great significance. However, it is becoming increasingly difficult to place significantly tighter limits on the existence of neutrino oscillations by means of accelerator experiments.

8. Particle Searches with Beam Dump

A major beam dump facility, the Direct Neutral Lepton Facility, has been designed for the Neutrino Area at Fermilab. A primary proton beam would be targeted on a dump just upstream of an active shield consisting of five large magnets. The shield was designed to minimize the muon background in the two bubble chamber detectors, the Tohoku chamber and the 15-foot chamber. They are located at distances of 58 m and 160 m from the dump target, respectively. Both of the bubble chambers will achieve high spatial resolution through the use of holography.

Two other detectors would look at the particles emerging from the beam dump: the fine-grained electronic neutrino detector located in Lab C at 200 m and an axion-search detector at 300 m.

The goals of the physics program with the Direct Neutral Lepton Facility are:

(1) The observation of the tau neutrino (ν_τ) via its interactions in the bubble chamber detectors.

(2) The search for unexpected phenomena, such as tau neutrino decays or axions, in the new energy range opened up by the Tevatron.

This is a physics program with unique opportunities. The detectors already exist for the most part. The cost of the Direct Neutral Lepton Facility is estimated to be $17 million. Funds have been requested to begin its construction in FY 1987 and to have the facility operational by FY 1989.

E. Non-Accelerator Experiments

Non-accelerator experiments differ widely in physics goals and techniques. Most are searches for exotic phenomena where positive results would be extremely important. Often, conventional physics does not predict an accessible level for the phenomena of interest; and therefore, negative results have much less impact. In addition, the effort and costs may increase sharply when one goes beyond a certain level of sensitivity.

Broadly speaking, the potential cost-benefit ratio of many of these efforts is extremely favorable. Such experiments should be given a high priority for support in the national program. In times of financial stringency, the rationale for support of expensive "second generation" efforts seems less compelling. These recommendations are illustrated and further defined in the following discussion of a few specific programs. This, however, is not meant to preempt conclusions which might be reached by a review to consider in more detail specific proposals in the light of these general guidelines.

Programs designed to determine the mass of the electron neutrino with an uncertainty of approximately 10 eV or less through the analyses of the tritium beta decay spectrum near the endpoint seem particularly desirable. Another attractive class of experiments is the attempt to observe neutrinoless double beta decay. Operation of the exceptionally successful IMB proton decay experiment should be given a high priority to exploit recent upgrades of the detector. In view of the successes of this experiment, other ongoing proton decay experiments are of somewhat lower priority. Without conclusive evidence for new phenomena in current experiments, proposals for new large proton decay experiments need to demonstrate new techniques to reduce costs and/or increase sensitivity substantially.

A galactic monopole flux greater than the Parker bound of about 1/100 m^{-2} sr^{-1} yr^{-1} would be expected to "short out" the magnetic field of the galaxy. The technically ingenious induction searches which have been conducted at a level of 10^5 times this level are thus searches outside most models of nature. It presently seems that any extension of such experiments to reach well beyond the Parker bound are exceedingly expensive. Indeed, lacking theoretical guides for the magnitude of monopole flux to be expected, from today's perspective high funding priority would not be appropriate for expensive monopole searches unless they are able to reach sensitivities far below the Parker limit.

F. Opportunities at Facilities in Related Fields

Many of the non-accelerator experiments that are now supported address problems of astrophysical interest. The importance of the deep relationship between cosmology and particle physics is widely recognized, and appropriate support of astrophysics programs which bear on particle physics, either directly or through their impact on cosmology, is recommended. In addition, novel interdisciplinary activities, whether accelerator-related or not, should not be penalized because they do not fall into conventional channels.

Brookhaven Laboratory has recently made a proposal to the Nuclear Physics Division of the Department of Energy to build a Relativistic Heavy Ion Collider (RHIC). This machine would produce colliding beams of nuclei up to gold with energies up to 100 GeV per nucleon. The central rapidity region of such collisions should contain the remnants of a possible plasma of quarks and gluons. Furthermore, the leading particles in such collisions will provide information on hot matter with high baryon density. The experimental signals for this phase transition are currently an active area of discussion.

Although this machine is in the realm of nuclear physics, it is of interest to the particle physics community. It will be directly testing non-perturbative aspects of the non-Abelian gauge theory of quarks and gluons.

SECTION IV

Transition to the Superconducting Super Collider

We are looking forward to the start of SSC construction in 1988 and an expected completion in 1994 after a 6-year construction period. In this Section, we describe a strong U.S. high energy physics program and show how the transition to the SSC might proceed. We look at "snapshots" of the program at three distinct times: in 1987, before the start of SSC construction; in 1991, during the SSC construction; and finally, in 1995, after the SSC has been completed and its operation for experiments has begun. Obviously, there are uncertainties associated with anticipating the program 10 years in the future in a rapidly moving field such as high energy physics. The following is our expectation from today's vantage point.

A. Evolution of the Research Program

1. The Program in 1987

By this time, the new facilities presently under construction will be completed. This will be the start of the rich utilization of all of our facilities. At Fermilab, the Tevatron I $\bar{p}p$ collider will be in early operation with one detector. The Tevatron II fixed-target programs will be in full operation. At SLAC, the e^+e^- collider, SLC, will be in its initial operation and PEP will be in full operation. The lower energy e^+e^- collider, SPEAR, will be utilized about half-time for high energy physics. At Brookhaven, the AGS will be in full operation. The majority of AGS time will be devoted to high energy physics, with a small portion of the time used by the nuclear physics program studying heavy ion collisions. At Cornell, the newly upgraged e^+e^- collider, CESR, will be fully utilized. There will also be a number of U.S. groups working at non-U.S. facilities. Detectors for the e^+e^- collider, LEP, and the $e^{\pm}p$ collider, HERA, will be under fabrication, and there should be experiments running at the e^+e^- collider, TRISTAN, and the $p\bar{p}$ collider, the $S\bar{p}pS$. A variety of non-accelerator experiments will be taking data. A vigorous SSC R&D program in advance of construction will be in progress, both on the accelerator systems and the associated detectors. There will also be activity in advanced accelerator R&D.

2. The Program in 1991

By this time, we expect the SSC will be in the middle of its construction period. The construction of detectors for the SSC will be in full swing. At Fermilab, the collider will operate with both major detectors and the full complement of fixed-target facilities, including the Direct Neutral Lepton Facility, will be utilized, both for experiments and for providing test beams for detector development. At SLAC, the SLC will be in full operation. At Brookhaven, a high intensity AGS with a completed Booster will be utilized partially by the high energy physics program and partially by the nuclear physics heavy ion program. At Cornell, CESR will still be operating. There will also be U.S. groups taking data in experiments at LEP and TRISTAN. Experiments at HERA, with U.S. participation, will be starting up. A variety of non-accelerator experiments will be taking data. The activity in advanced accelerator R&D will be increasing.

3. The Program in 1995

By this time, we expect that the SSC will be in its early stages of operation with at least a partial complement of detectors. At Fermilab, we expect that the collider will be running with a mature program; the fixed-target facilities will be operating for an experimental program at a reduced level in addition to supplying test beams for new detector development. The SLC at SLAC will still be in operation. The AGS at Brookhaven is expected to be almost fully occupied as an injector for the heavy ion collider, RHIC, and as a fixed-target facility for the nuclear physics program and is not expected to be utilized significantly by the high energy physics program. U.S. groups will probably still be involved at LEP II and HERA, but the TRISTAN involvement is expected to be winding down. A variety of non-accelerator experiments will be taking data. We anticipate a vigorous program in advanced accelerator R&D at this time. It will be difficult to maintain a forefront U.S. program if the operation of the SSC is delayed beyond this time.

B. Funding Required for the High Energy Physics Program

An estimate has been compiled for a minimum budget required to carry out the program described in this report. For the pre-SSC program in FY 1987, these estimates are $435 million for operating, $90 million for equipment, $70 million for construction (for a total of $595 million non-SSC related) and $65 million for SSC R&D, for a total high energy physics budget from the DOE of $660 million. An additional $55 million is required from the National Science Foundation (all in FY 1987 dollars). For comparison, the FY 1985 High Energy Physics budget (converted to FY 1987 dollars) was $400 million in operating, $66 million in equipment, and $129 million in construction, (for a total of $595 million non-SSC related) and $23 million for SSC R&D, for a total DOE budget of $618 million, with an additional $46 million from the NSF. We note that while the total non-SSC related funds needed for FY 1987 are essentially the same as in FY 1985, the operating funds are up and the construction funds are down relative to FY 1985. This is necessary for the following reasons. Two of the major accelerator facilities of the high energy physics program will be coming into full operation by 1987. These unique state-of-the-art accelerators (SLC and Tevatron) are not only the mainstay of the high energy physics program but also prototypes for future higher energy accelerators. It is essential that incremental operating funds be provided for these facilities.

With these assumptions, the projection of the DOE High Energy Physics budget to FY 1995 is given in Table IV-1. Here the SSC construction, equipment, and operating costs from the SSC Reference Designs Study have been used. It can be seen that a substantial pulse of incremental funding over the FY 1987 level is required for the SSC construction for the FY 1988 to FY 1993 period. After this period, the funding required for the program, including the operation of the SSC, returns to within about 10 percent of the FY 1985 level. During the SSC construction period, the non-SSC part of the budget declines, reaching a reduced level of about $400 million by FY 1995. The SSC operating costs are expected to be $215 million with an additional $50 million in equipment funds and $15 million in accelerator improvement (AIP/GPP) funds, for a total high energy physics budget from the DOE of about $680 million in FY 1995 (in FY 1987 dollars).

C. Scientific Manpower

Current estimates indicate that the U.S. scientific manpower (Ph.D physicists or equivalent) working in high energy physics at the present time consists approximately of 1,150 experimentalists, 750 theorists, and 330 accelerator scientists. The number of experimentalists now occupied in carrying out the present program is not a bad match to the requirement of the program during the SSC construction period and the period after the start of SSC operation. We do, however, anticipate a scarcity of accelerator physicists during the SSC construction period. A need for a 20 to 30 percent increase in the number of accelerator scientists is nticipated. A vigorous program of training present high energy physics xperimentalists and theorists in accelerator science is of high importance n the near future. In addition, efforts should be made to make a career in ccelerator physics attractive to young physicists entering the field of igh energy physics. We anticipate a flow of experimentalists and ccelerator physicists from the present program to the program including the

SSC. We expect that in addition to the U.S. physicists, there will be a substantial number of non-U.S. experimentalists working at the SSC. This analysis shows that the existing high energy physics manpower, with an anticipated 10 percent growth over the next decade, can accomplish the program described in this report.

Table IV-1

Projected High Energy Physics Budgets
1985 - 1995
(in units of millions of FY 1987 dollars)

	FY 85	FY 87	FY 91	FY 95
Non-SSC Program				
Operating*	$400	$435	$ 410	$350
Equipment	66	90	70	40
Construction	129	70	20	10
Total Non-SSC	$595	$595	$ 500	$400
SSC Program				
R&D	$ 23	$ 65	$ 40	$ 0
Construction			700	15
Equipment			130	50
Operating			30	215
Total SSC	$ 23	$ 65	$ 900	$280
Total DOE Program	$618**	$660	$1400	$680
NSF	$ 46	$ 55	$ 48	$ 48

* Includes university budgets, part of which will be spent on SSC experiments.

**546 in FY 85 dollars

SECTION V

Advanced Accelerator R&D

Progress in high energy physics accelerators is often shown in a "Livingston plot" which shows an exponential growth of energy with time. This growth has been achieved by an alternation between the development of a particular technology and the introduction of a new one.

The storage ring technique has been the key to the energy advances of the last decade. There are now many successful e^+e^- and hadron-hadron colliders. Two machines, Tevatron I and LEP, are under construction to be major facilities in the next decade. Such storage rings, however, appear to be reaching their ultimate energy. LEP is forced by synchrotron radiation considerations to a circumference of 27 km. The proposed SSC, because of magnetic field constraints, would have a circumference of approximately 100 km. These are at the limits of practical size.

Progress beyond the 200 GeV center-of-mass energy of LEP and 40 TeV center-of-mass energy of SSC will require new acceleration techniques. At this time, there are no practical ways to either avoid the synchrotron radiation in e^+e^- machines, nor to use economically significantly higher magnetic fields in proton rings. Linear colliders such as the SLC offer the possibilities of much higher energies for both electrons and protons, but the existing technology would be prohibitively expensive in or above the TeV range.

In response to this challenge, and following the recommendation of the HEPAP Subpanel on Accelerator Research and Development, the efforts to find new acceleration methods have been expanding. These efforts range from relatively modest extensions of technology to the exploration of new physical phenomena. The emphasis has been on exploring as wide a range of ideas as possible.

Work on superconducting cavities is being pursued at Cornell, and some work on very high field magnets is contained in the normal accelerator R&D programs. The main efforts, however, in the advanced accelerator field have been to explore power sources and acceleration schemes for high gradient linear devices.

Power source development is aimed at higher efficiency, higher peak power, and shorter wave length sources. Work on laser driven klystrons is under way at SLAC and in Japan. The SLAC effort includes studies of new pulse compression schemes and the study of breakdown limits. Work on gyrotrons is being done at the University of Maryland. We are particularly encouraged by the success of the LBL-Livermore collaboration in achieving very high power and good efficiency in a Free Electron Laser (FEL). This group has proposed a "Two Beam Accelerator" employing a continuous sequence of acceleration and FEL sections in a low energy beam providing power to a parallel high energy linac.

The generation of very short, single cycle pulses of rf power is being studied. Wakefields from a single high current bunch have been considered in Japan, at ANL, and at DESY. At DESY, a ring bunch is being used in a "wakefield accelerator" currently under test. At ANL, a wakefield research test set-up is being added to a short pulse 22 MeV electron linac. Single pulses generated by power switching are being considered at Rochester (solid state switch), at CERN and BNL (photodiode switch), and in Texas (Blumlein).

The use of lasers has been considered by many groups. Lasers, despite their relatively low efficiency, offer higher instantaneous powers than any other available source and, thus, the possibility of very high fields. At BNL, Cornell, LANL, SLAC, and NRC Canada, progress has been made in understanding "open", grating like, linac cavities that could be used with both lasers and more conventional sources. Inverse free electron lasers (discussed by many groups) and inverse Cherenkov acceleration (observed at Stanford) seem unsuitable for high energy acceleration, but may be important for injection, bunching and focusing. Very encouraging progress has been made on the plasma beat wave accelerator proposed at UC-Los Angeles and Texas. Intense laser excited plasma oscillations have been observed at UC-Los Angeles, and modeling of acceleration with such waves performed at UC-Los Angeles, Texas, and LANL. Plasma waves excited by beam pulses have been proposed at UC-Los Angeles, modeled at UC-Los Angeles and SLAC, and may be studied experimentally at Argonne National Laboratory.

Much of the work described above has been of a theoretical or exploratory type. There seems to be no lack of ideas, though new ones are always welcome. More work is now needed on real experimental demonstration. This will require a significant increase in funding above its present level of approximately $7 million per year; an increase HEPAP strongly endorses.

The emphasis up to now has been on encouraging a wide range of new initiatives without being too critical about their application to a real collider design. This has been necessary. However, the time for such serious study has come. Within the next few years one or two ideas should be ready for more active and directed development toward a very high energy facility. Between $5 and $10 million per year may be required for this work, in addition to continued funding for the more speculative ideas. Even with this further increase, the total funding (on the order of $20 million) would not exceed the 4 percent recommendation of the HEPAP Subpanel on Accelerator Research and Development (DOE/ER-0067).

On a longer time scale, we should expect a proposal for a demonstration linear collider in the 100 GeV range. It must be emphasized that we do not,

at this time, know that the required technology will exist. Even if identified, this technology will be new and interesting, but very uncertain. Such a demonstration machine, though of great importance to the future of the field, cannot be regarded as a facility for the high energy physics community and in no way alters the need and importance of the SSC.

SECTION VI

International Collaboration

High energy physics is truly an international scientific enterprise, with a long history of the exchange of ideas, people, and equipment. In addition to informal agreements, for example, between groups in the United States and in Western Europe, cooperative agreements between countries have been formalized to expedite exchanges. Examples of formal bilateral agreements involving the United States include agreements with the Soviet Union, with Japan, and with the People's Republic of China. Over the past 30 years, Western Europe has been enormously successful in consolidating the efforts of European particle physicists at CERN, whose facilities in Geneva, Switzerland, are now utilized by about 2,500 researchers from 13 Member States plus about 500 other physicists from non-Member States.

The level of international collaboration is actually much greater than indicated by formal agreements, and practice on large experiments today pools the talent and resources from several countries, whether or not they fall under formal bilateral agreements. There are over 60 foreign institutions involved in approved experiments in Fermilab's Tevatron II fixed-target program. Presently, there appear to be between 200 and 300 U.S. physicists involved in experiments abroad and more than 400 foreign scientists participating in experiments at U.S. laboratories. The available data suggests, moreover, that there is approximate parity in the exchange of capital equipment between the U.S. and other countries.

HEPAP reiterates its support for an open policy. It is the accepted practice at major accelerator laboratories throughout the world to accept proposals from any group, domestic or foreign. Approval and support have been and should continue to be judged on the basis of scientific merit and available resources through the usual peer review processes. DOE and NSF should continue to support U.S. participation in foreign programs whenever justified by the physics objectives and opportunities.

As detectors grow larger and the world's accelerator facilities become more individually unique in their capabilities, these exchanges of researchers become increasingly important in order to provide a full scope of opportunities for U.S. and foreign experimenters. Improved contractual or international agreements are necessary to facilitate the exchanges of personnel and equipment. These could, for example, expedite visa and customs formalities.

Other opportunities will arise in the future for collaboration in accelerator construction; for example, the mode established by DESY with HERA. We endorse securing international participation in all phases of the SSC project, commensurate with the goals of the U.S. High Energy Physics program. Another area ripe for increased collaboration is the anticipated expansion of advanced accelerator research and development on new technologies for particle acceleration in the post-SSC era.

We note the inclusion of high energy physics in the Summit process and appreciate the efforts of the heads of state of the participating countries to facilitate international cooperation and to remove administrative obstacles to effective collaboration in science and technology.

SECTION VII

Conclusions and Recommendations

Conclusions

The physics justification for a multi-TeV high-luminosity hadron-hadron collider is even stronger today than it was in 1983 at the time of the original HEPAP recommendation. The technical successes achieved by the SSC R&D program in the intervening two years reinforce confidence that this facility can be built within the costs and on the time scale estimated in the Reference Designs Study.

We strongly reaffirm the SSC as the highest priority in the U.S. High Energy Physics program. A project of the magnitude of the SSC will clearly cause major redirection of resources during the next 10 years. However, there is no alternative to such a project for reaching the scientific objectives which are essential for the progress of the field. Further, we believe that it is possible to achieve a reasonable transition into the SSC program. Some of the existing programs will be terminating just as extensive experimental effort on SSC detectors will need to commence. The timely completion of the SSC will provide a truly forefront facility for the world's high energy physics community. We must point out, however, the inevitable deterioration of the U.S. program and the difficulty of maintaining continuity of the field if the SSC were delayed appreciably beyond the presently anticipated time scale. If this were the case, there would be no frontier facility in high energy physics in the U.S. in the mid-1990s.

We have evaluated the physics opportunities in the program for the period of approximately 10 years before the SSC would come into operation. These opportunities provide for a rich physics program with excellent prospects for fundamental advances. The superconducting Tevatron II at Fermilab has recently come into operation at an energy of 800 GeV, the highest energy fixed-target facility in the world. The Fermilab Tevatron I Collider will become operational in 1987 and will be the world's highest energy hadron collider extending the energy range from 0.6 TeV now (at the CERN S$\bar{p}$pS) to 1.8 TeV. The SLC, which will come into operation in 1987 at the Stanford Linear Accelerator Center, will be the first e^+e^- collider to reach the energy of the $Z°$ and also represents a pioneering effort toward a new class of electron-positron colliders.

These opportunities also include important programs at new facilities abroad. The CERN project, LEP, will become operational for physics in 1989 and will provide e^+e^- collisions initially in the $Z°$ range and later at higher energies up to 100 GeV per beam. The TRISTAN project in Japan will become operational for physics in 1987 providing e^+e^- collisions up to a total energy of about 60 GeV. There will be major U.S. participation in research at both of these projects. The HERA project at DESY will become operational in 1990 with $e^{\pm}p$ collisions up to a center-of-mass energy above 300 GeV, opening new opportunities for research.

The Panel has identified a limited number of programs which, because of their intrinsic importance, their likely impact on the course of future research, and their key role in the U.S. program, should proceed with priority. The Panel places in this category: The CDF and DØ projects at Tevatron I, the L3 project at LEP, the Mark II and SLD projects at SLC, the CESR program. The Panel also considers the smaller scale efforts involving studies of CP violation with kaons, high sensitivity studies of rare kaon decays, and certain parts of the non-accelerator program as enumerated in Section III.E to be in this category. However, to realize the opportunities which will be available in the next ten years and to utilize properly the facilities which will exist, adequate support must be provided to the full physics research program. This is a broadly based forefront program providing essential diversity and scope.

Finally, we note the importance of maintaining and strengthening the technology research in advanced accelerator R&D. This research, as noted in Section V., is essential to the long term progress of the field.

Recommendations

1. We recommend that the SSC R&D be given highest priority in the U.S. High Energy Physics program so that the project can proceed to an early construction start and rapid completion. In particular, for FY 1986, we support the requested incremental allocation of $7 million to SSC R&D, primarily so that early substantial industrial involvement in the magnet R&D effort can be initiated.

2. We recommend that the limited category of forefront programs identified in the report proceed with priority.

3. We recommend that the overall funding be adequate to permit the effective implementation of the broadly based program providing essential diversity and scope with high priority to the special programs, and to pursue the crucial SSC R&D effort.

   Comment: For FY 1987 this would require a small increase beyond the FY 1985 total level of effort. With reduced construction activity, this would allow the increased funding required for the utilization of the new capabilities coming into operation (the SLC at SLAC and the Tevatron at Fermilab) and for the SSC R&D effort.

   It is clear that construction of SSC and fabrication of detectors for SSC will require incremental funding above this level. A funding profile such as shown in Section IV would ensure the scientific vitality and stature of the U.S. High Energy Physics program during the period prior to SSC operation. After the SSC is completed, it appears that an excellent program, including the SSC and a reduced non-SSC program, could be supported at a funding level about 10 percent above the current (FY 1985) level of effort.

4. We recommend that advanced accelerator R&D be strongly supported. A continued and strengthened effort in this area is essential to the long-term progress of the field.

APPENDIX A-1

Participants in the 1985 HEPAP Study

Membership

R. Adair - Yale University
C. Baltay - Columbia University
M. Creutz - Brookhaven National Laboratory
H. Edwards - Fermi National Accelerator Laboratory
M. Einhorn - University of Michigan
G. Feldman - Stanford Linear Accelerator Center
H. Grunder - Continuous Electron Beam Accelerator Facility
J. D. Jackson - Lawrence Berkeley Laboratory and University of California at Berkeley
P. F. M. Koehler - Fermi National Accelerator Laboratory
R. B. Palmer - Brookhaven National Laboratory
J. Peoples, Jr. - Fermi National Accelerator Laboratory
J. Sandweiss, Chairman - Yale University
R. Siemann - Cornell University
S. C. C. Ting - Massachusetts Institute of Technology
B. Winstein - University of Chicago
S. Wojcicki - Stanford University
P.K. Williams, Executive Secretary - Department of Energy

Technical Consultants to the Working Groups

B. Barish - California Institute of Technology
E. Berger - Argonne National Laboratory
J. Cumalat - University of Colorado
E. Eichten - Fermi National Accelerator Laboratory
T. Gaisser - Franklin Institute
L. Littenberg - Brookhaven National Laboratory
A. Melissinos - University of Rochester
F. Merritt - University of Chicago
H. Montgomery - Fermi National Accelerator Laboratory
M. Perl - Stanford Linear Accelerator Center
P. Slattery - Rochester University
G. Steigman - Franklin Institute

APPENDIX A-2

1985 HEPAP Summer Study

Working Groups

1. e^+e^- Facilities (C. Baltay, G. Feldman, S. Ting)

2. Fixed-Target Facilities (P. Koehler, R. Palmer, B. Winstein)

Proton-Antiproton Colliders and Electron-Proton Colliders (M. Einhorn, J. Peoples)

SSC (J. D. Jackson, R. Siemann, S. Wojcicki)

Accelerator Operations and Advanced Accelerator R&D
(H. Edwards, H. Grunder, R. Palmer)

Non-Accelerator Physics and Interfaces with Other Fields
(R. Adair, M. Creutz)

Organization, Budget Scenarios, and Manpower
(C. Baltay, P. Koehler, J. Sandweiss)

APPENDIX A-3

Information Gathering Meeting

Working Group on Accelerator Operations and Advanced Accelerator R&D

Brookhaven National Laboratory
Upton, NY

April 22-23, 1985

The Working Group was given the following presentations:

SLAC Accelerator Operations, SLC, Accelerator R&D	E. Paterson (SLAC)
Cornell Accelerator Operations, CESR Upgrade, R&D	R. Siemann (Cornell Univ.)
DESY Accelerator Operations, HERA, Accelerator R&D	V. Soergel (DESY)
Fermilab Accelerator Operations, Tevatron I, Accelerator R&D	R. Orr (Fermilab)
Argonne General Accelerator Work and R&D	J. Simpson (ANL)
LBL General Accelerator Work and R&D	K. Berkner
BNL Accelerator Operations, Booster, RHIC, Accelerator R&D	H. Foelsche D. Lowenstein T. Ludlam Y. Y. Lee (BNL) S. Schriber (LANL)
LANL, LAMPF II, Accelerator R&D	S. Schriber (LANL)
AAR&D, Collider Scaling, Survey of Acceleration	R. Palmer (BNL)
Techniques, Grating and Beat Wave Acceleration	C. Joshi (UCLA)

APPENDIX A-3

Information Gathering Meetings

Working Group on Non-Accelerator Physics
and Interfaces with Other Fields

Brookhaven National Laboratory
Upton, NY

April 22-23, 1985

e Working Group was given the following presentations:

L Presentation on Non-Accelerator Physics and Interactions with Other Fields	H. Satz T. L. Trueman T. Ludlam (BNL)
B Proton Decay	D. Sinclair (Univ. of Michigan)
oton Decay; World Data	J. LoSecco (Caltech)
UDAN II	M. Marshak (Univ. of Minnesota)
ort of the Subpanel on Computer Needs or the Next Decade	J. Ballam (SLAC)
uctive Monopole Searches	B. Cabrera
-Inductive Monopole Searches	B. Barish (Caltech)
AND	J. Learned (Univ. of Hawaii)
ic Rays; Gammas	G. Cassiday (Univ. of Utah)
le Beta Decay	W. Witherall (Princeton Univ.)
ium end point	O. Fackler (Rockefeller Univ.)

APPENDIX A-3

Information Gathering Meeting

U.S. and Foreign Laboratory Directors Meeting

National Academy of Sciences
Washington, DC

April 24, 1985

The Working Group was given the following presentations:

Status and Future Plans at KEK	S. Ozaki
Status and Future Plans at DESY	V. Soergel
Status and Future Plans at CERN	G. Brianti
Report on Activities of ECFA	J. Sacton
Status and Future Plans on SSC	M. Tigner
Status and Future Plans at SLAC	B. Richter
Status and Future Plans at Fermilab	L. Lederman
Status and Future Plans at BNL	N. Samios
Status and Future Plans at CESR	B. McDaniel

APPENDIX A-3

Information Gathering Meeting

Working Group on Proton-Antiproton and Electron-Proton Colliders

Fermi National Accelerator Laboratory
Batavia, IL

May 8-9, 1985

The Working Group was given the following presentations:

CERN S$\bar{p}$pS	
The S$\bar{p}$pS Upgrade	F. Pedersen (CERN)
S$\bar{p}$pS Experiment Program	W. Kienzle (CERN)
UA-1 Upgrade and its Physics Program	J. Rohlf
Fermilab Tevatron I	
Parameters of Tevatron I and Plans for Future Upgrade	R. Orr (Fermilab)
The Tevatron I Experimental Program	F. Nezrick (Fermilab)
The CDF Detector and its Physics Program	R. Schwitters (Harvard/Fermilab)
The D0 Detector and its Physics Program	P. Grannis (SUNY--Stony Brook)
Comments from the Director of Fermilab	L. Lederman
DESY/HERA	
HERA: The Machine and Its Physics Program	R. Peccei P. Soding (DESY) W. Y. Lee (Columbia Univ.) I. Pless (MIT)

APPENDIX A-3

Information Gathering Meeting

Working Group on Fixed-Target Facilities

Fermi National Accelerator Laboratory
Batavia, IL

May 8-9, 1985

The Working Group was given the following presentations:

The Brookhaven AGS Program

Introduction	R. Palmer (BNL)
Rare Kaon Decay	L. Littenberg (BNL)
Neutrino Physics	W. Y. Lee (Columbia Univ.)
Polarized Proton Physics	A. Krisch (Univ. of Michigan)
Heavy Ion Physics	R. Palmer (BNL)

Planned Kaon Factories

LAMPF II	G. Garvey (LANL)
TRIUMF II	A. Astbury (Univ. of Victoria)

The SLAC & CERN Fixed-Target Programs

Opportunities for Fixed-Target Experiments at SLAC	R. Taylor (SLAC)
The CERN Fixed-Target Program	F. Dydak (CERN)

The Fermilab Tevatron II Program

Introduction	L. Lederman (Fermilab)

The Fermilab Tevatron II Program (cont'd).

QCD Physics	T. Ferbel (Univ. of Rochester)
Heavy Quark Physics	J. Butler (Fermilab)
Lepton Scattering	H. Montgomery (Fermilab)
Outlook	J. Bjorken (Fermilab)

KEK Fixed-Target Program

KEK--High Energy Physics Program with Stationary Target (written submission)	S. Ozaki (KEK)

APPENDIX A-3

Information Gathering Meeting

Working Group on Electron-Positron Colliders

Stanford Linear Accelerator Center
Stanford, CA

May 23-24, 1985

The Working Group was given the following presentations:

SLAC Plans	B. Richter (SLAC)
LEP Storage Ring	E. Picasso (CERN)
ALEPH, DELPHI, and OPAL	U. Amaldi (CERN)
L3	S. Ting (MIT)
SLD	C. Prescott (SLAC)
Mark II at SLC	J. Dorfan (SLAC)
TRISTAN	S. Ozaki (KEK)
AMY	S. Olsen (Univ. of Rochester)
PETRA	G. Wolf (DESY)
PEP	P. Oddone (LBL)
CESR	B. Gittelman (Cornell Univ.)
DORIS	G. Wolf (DESY)
SPEAR	W. Toki

APPENDIX A-3

Information Gathering Meeting

Working Group on SSC R&D

Stanford Linear Accelerator Center
Stanford, CA

May 23-24, 1985

The Working Group was given the following presentations:

SSC CDG and National Activities	S. Wojcicki (SSC-CDG)
Laboratory Efforts and Magnet Selection	T. Elioff (SSC-CDG)
SSC	M. Tigner (SSC-CDG)
SSC Detector R&D Requirements	M. Gilchriese (Cornell)
evelopments in Superconducting Magnets	C. Taylor (LBL)

APPENDIX 8

High Energy Physics Accelerator Facilities

I. United States

A. Fermilab (Batavia, Illinois)

The Tevatron accelerator operates as a proton accelerator for fixed-target experiments and as a storage ring for p-$\bar{p}$ collisions.

1. Tevatron (Tevatron II) Fixed-Target Proton Accelerator

Present operation is at 800 GeV and 1.3×10^{13} protons per pulse. Cycle time is 60 sec with a 20 sec spill to 8 primary slow spill beam lines. In addition, fast spill is delivered for experiments. Operation with slow spill to 2×10^{13} protons per pulse and 900 GeV may be obtained by 1987-1988. The accelerator will be off in FY 1986 to finish construction for Tevatron I.

2. Tevatron (Tevatron I) p-$\bar{p}$ Collider-Storage Ring and $\bar{p}$ Source

The collider is presently being commissioned. Initial operation at 900 GeV per beam is planned for 1987. The design luminosity is 10^{30} cm^{-2} sec^{-1}. The nominal $\bar{p}$ source production rate is 10^{11}/hr. Only one detector (CDF) will be operational prior to the end of 1989 when the second (D0) detector will begin operation. Luminosity and energy upgrades are planned.

Beginning in FY 1987 operation time of fixed-target and collider programs is planned for at least five months each.

B. SLAC (Stanford, California)

Three accelerators, PEP, SPEAR, and the Linac are presently operating at SLAC. The SLC is under construction.

1. PEP e^+e^- Collider-Storage Ring

Present operating energy is at 14.5 GeV per beam with an average luminosity of 1 pb^{-1} per day. An upgrade of the low-beta region to be completed by mid-1987 would improve the luminosity by a factor of 3 to 4. PEP will not operate during most of 1986 in order to commission SLC.

2. SPEAR e^+e^- Collider-Storage Ring

Present operating energy is 1.5 to 3.7 GeV per beam with a luminosity of approximately 0.1 pb^{-1} per day. A low-beta upgrade has recently been installed which should increase the luminosity by a factor of three. The machine operates for both high energy physics and synchrotron radiation research.

3. Linac e^- Fixed Target Physics

The Linac operates at 30 GeV for fixed-target physics and test beams. Higher energy (approximately 50 GeV) will be available in the near future.

4. SLC e^+e^- Linear-Collider

SLC is under construction at this time. Initial operation is scheduled to begin in January 1987. The energy is 47 GeV per beam and luminosity should increase from 5 x 10^{28} cm^{-2}/sec to 6 x 10^{30} cm^{-2}/sec during the time period to the mid-1990s. This collider has one interaction region. Operation is planned for 30 weeks per year.

C. BNL (Upton, NY)

1. AGS - Fixed-Target Proton and Heavy Ion Accelerator

Present operation is at 29 GeV for protons and 14.6 GeV per atomic mass unit for heavy ions. Both polarized and unpolarized protons are available with intensities of a few x 10^{10} for polarized protons and 1.0 - 1.6 x 10^{13} for unpolarized protons per AGS cycle. Intensities for heavy ions range from 2.5 x 10^{10} for oxygen to 2.5 x 10^{8} for sulfur. The cycle time of the AGS is 1.2 to 3 seconds, depending on whether fast or slow extraction is used. For slow extraction the duty cycle is 50 percent. There are two fast and seven slow primary beam lines to the experimental areas.

The AGS Booster upgrade planned for operation in 1989 will increase the polarized proton intensity by a factor of 20, the unpolarized proton intensity by a factor of 4, and will provide for acceleration of heavy ions up to gold.

D. Cornell University (Ithaca, NY)

1. CESR e^+e^- Collider-Storage Ring

Present operation is in the energy region of 4.5 to 5.6 GeV per beam with 3 to 7 bunch operation. Average luminosity is 4 pb^{-1} per week and 6.5 pb^{-1} per week has been obtained with 7 bunches.

An upgrade expected in January 1986 consists of a new micro-beta interaction region with a possible luminosity increase of a factor of two.

II. Western Europe

A. CERN (Geneva, Switzerland)

The SPS proton accelerator at CERN operates for both fixed-target and collider physics. The PS which has been extensively used for experiments, is now used as part of the injector chain for the SPS and LEP accelerators. A low energy antiproton ring, LEAR, has been in operation since mid-1983. The large e^+e^- storage ring, LEP, is under construction.

1. PS Injector, Fixed-Target Proton Accelerator

The PS is the injector for the AA, LEAR, and the SPS. Extracted beam from the PS is also used for experiments and test beams. The PS operates at 26 GeV/c for external beams. The intensity is 2.2 x 10^{13}ppp with a cycle time of 1.5 sec. The PS will also be used for light ion (O^{16}) acceleration for SPS injection.

2. SPS

The SPS operates as a proton accelerator for fixed-target experiments and as a storage ring for p-$\bar{p}$ collisions (S$\bar{p}$pS). It will also serve as an injector of e^{+-} to LEP.

3. SPS Fixed-Target Proton Accelerator

Operation is at 450 GeV with intensities of 3×10^{13} protons per pulse with a 14 sec cycle rate. These protons are used to provide beams of different particle types in two main areas. Some of these beams are used as test beams for LEP experiments, later for HERA experiments. It also is planned to accelerate light ions to 225 GeV per atomic mass unit in the SPS.

4. S$\bar{p}$pS - p$\bar{p}$ Collider-Storage Rings

Typical operation is at 315 GeV per beam with an average luminosity of 0.1×10^{30} cm^{-2} sec^{-1} with three bunch on three bunch collisions. A peak luminosity of 0.35×10^{30} cm^{-2} sec^{-1} has been reached. Excursions to 450 GeV per beam have been made. The $\bar{p}$'s are accumulated in the antiproton accumulator source ring at a rate of 7×10^{9} $\bar{p}$ per hour.

An improvement in luminosity is planned. The construction of a precooling source ring, ACOL, will increase the $\bar{p}$ accumulation rate by a factor of 10. Especially, new rf (100 MHz) in the SPS will double the longitudinal acceptance and the number of bunches in the SPS will be increased to six. Nominal luminosity after these upgrades is 4×10^{30} cm^{-2} sec^{-1} and should be achieved in 1987 to 1988.

5. LEAR

The antiprotons stored in the antiproton accumulator can be decelerated in the PS and sent into the low energy antiproton ring. They are then ultra-slowly ejected producing some 10^5 particles per second during periods of 15 minutes or more. The momentum of the antiprotons presently can be varied from 0.2 to 1.5 GeV/c.

6. LEP e^+e^- Collider-Storage Ring

LEP is under construction at this time. Initial operation is planned for 1989. Nominal energy per beam is 55 GeV with a luminosity of 1.6×10^{31} cm^{-2} sec^{-1} with four bunches.

An upgrade using superconducting rf cavities will increase the energy per beam to 75-100 GeV and then up to 100 GeV. Energies of 100 GeV per beam could be available by 1993.

7. Possible Future Projects

Currently CERN is studying the most effective use of its investments, in particular the LEP tunnel and the existing accelerators. The time scale for this study is the next two years. It is expected that a design of a large hadron collider will evolve based on the superconducting magnet technology of Fermilab and DESY, among others. The energy which can be reached is dependent on the success of the magnet R&D program. A reasonable generic machine design indicates that roughly 0.9 TeV can be reached per Tesla of magnetic field in the dipoles. Because of the existing LEP Ring, e-p, $\bar{p}p$, or pp collisions may be studied depending on whether or not two rings are added to the LEP ring.

B. DESY (Hamburg, West Germany)

Two e^+e^- storage rings are presently in operation. An $e^\pm p$ storage ring (HERA) is under construction.

1. PETRA e^+e^- Collider-Storage Ring

Present operation is at 22 GeV per beam with a luminosity of 0.2 pb^{-1} per day and two bunches per beam.

In 1987 it will be turned off and converted to the injector for HERA. Electrons will be accelerated to 14 GeV and protons to 40 GeV in PETRA.

2. DORIS e^+e^- Collider-Storage Ring

Operation is at 5.4 GeV per beam. Luminosity is 1.0 pb^{-1} per day with one bunch per beam. DORIS operates 7 to 9 months per year with 2/3 of the time used for high energy physics and the rest for synchrotron light source operation.

3. HERA e^+e^- Collider-Storage Ring

HERA is under construction and will begin operation in 1990. Nominal energy for the e beam is 30 GeV and for the proton beam is 820 GeV.

Superconducting magnets will be used for the proton ring. The nominal luminosity is 3×10^{31} cm^{-2} sec^{-1}. Initial electron operation will be at 27 GeV. Upgrades using superconducting rf are planned to increase the $e^\pm$ energy to 30-35 GeV. Polarized electron beams (80%) are also planned.

III. Japan

A. KEK (Tsukuba)

KEK has a 12 GeV proton synchrotron preceded by a 500 MeV Booster. The Booster is also used for cancer therapy and neutron and solid state physics. TRISTAN, an e^+e^- collider is presently being constructed. It is preceded by an 8 GeV e^+e^- accumulator ring which is also used for detector calibration.

1. PS Fixed-Target Proton Accelerator

The PS has been off for construction related to TRISTAN. Operations will resume in 1985 at 12 GeV for protons. Intensity prior to the shutdown in 1984 was 4×10^{12} protons per pulse. Increased intensity of a factor of 2 to 3 is expected with the resumption of operation. Cycle time is 2 seconds. Polarized proton beam development is under way.

2. TRISTAN e^+e^- Collider Storage Ring

TRISTAN is a e^+e^- collider with a design goal of 30 GeV per beam which is under construction. Initial operation is planned for late 1986 at 22 to 25 GeV. The installation of superconducting rf could bring the energy to 36 GeV. Design luminosity is in the range of 3 to 8×10^{31} cm^{-2} sec^{-1}. The accumulator ring is completed and operating.

IV. USSR

A. IHEP (Serpukhov)

Presently U-70, a 76 GeV proton synchrotron, is available for high energy physics. This accelerator will be used as an injector to UNK's Stages I and II that are under construction, and will provide fixed-target physics at 3 TeV and $\bar{p}$-p collisions at 2.2 TeV center-of-mass.

1. U-70 Fixed-Target Proton Accelerator

This accelerator has been operating at 76 GeV energy and 2.2×10^{12} protons per pulse, and cycle time of approximately 7 seconds. With the addition of a Booster ring between the Linac and U-70, intensities of 5×10^{13} protons per pulse are expected. Operation with the new Booster has just started.

2. UNK Stage I Proton Accelerator-Storage Ring

UNK is a proton accelerator-storage ring which is under construction. Design maximum energy is 400-600 GeV and the nominal intensity is 6×10^{14} protons per pulse. This accelerator has conventional iron magnets. The accelerator circumference is 21 km.

3. UNK Stage II Proton Accelerator-Storage Ring

This is a planned superconducting magnet accelerator located in the same tunnel as Stage I. Nominal energy is 3 TeV and nominal intensity is 6×10^{14} protons per pulse. Cycle time for fixed-target physics is 78 seconds with 38 sec flattop. In storage mode, $\bar{p}$-p collisions between Stages I and II are planned and will yield a nominal luminosity of 10^{32} cm^{-2} sec^{-1}. Construction completion is expected in the early 1990s.

Further proposals include the addition of a second 3 TeV ring and a source.

B. INP (Novosibirsk)

1. VEPP-4 e^+e^- Collider-Storage Ring

Maximum energy is 5.8 GeV per beam. Luminosity of 3 x 10^{30} cm^{-2} sec^{-1} has been obtained at 5 GeV. Polarized beams of over 50 percent have been achieved.

C. JINR (Moscow)

The 10 GeV synchrophasotron is used mainly for heavy ions.

V. People's Republic of China

A. IHEP (Bejing, PRC)

1. BEPC e^+e^- Collider-Storage Ring

BEPC is an e^+e^- collider-storage ring with design energy per beam of 2.2 to 2.8 GeV which is currently under construction. Nominal luminosity is 1.7 x 10^{31} cm^{-2} sec^{-1} with one bunch per beam. Initial operation is expected in 1988. The accelerator will also be used for synchrotron radiation experiments.

APPENDIX 4

SSC MAGNET SELECTION ADVISORY PANEL

REPORT TO THE DIRECTOR OF THE CENTRAL DESIGN GROUP

September 9, 1985

I. INTRODUCTION

The Magnet Selection Advisory Panel (MSAP) was appointed by the Director of the Central Design Group (CDG) to assist in the selection of the SSC magnet type from a set of five proposed basic magnet styles. The Panel and its Consultants met for four days, August 25-28, 1985, at the URA Design Center, Lawrence Berkeley Laboratory, and heard testimony from proponents of the various styles. Each group of proponents was permitted to bring five participants to the meeting. Members of the CDG presented technical and cost analysis summaries excerpted from their various reports. In addition, representatives of the Department of Energy and the scientific community, including epresentatives of the Board of Overseers, were invited to attend. Appendix A rovides the list of members of the MSAP, consultants, and other partici- ants. The specific charge to the MSAP was "...submit a report to the irector containing the Panel's recommendation in the form of an ordered list these five basic magnet styles...," based on a set of Criteria provided by e CDG. Appendix B provides the complete Charge, set of Criteria, and CDG mments on the Criteria. Comprehensive documentation, as listed in pendix C, was provided to the MSAP in advance of the meeting. Adequate time provided for presentations by the proponents and CDG staff and for full cussion of all relevant issues. The agenda is shown in Appendix D. Writ- materials given to the Panel during the meeting are listed in Appendix E.

The MSAP was asked to consider the five basic magnet types:

I) (Style C) Low-field superferric, mechanically and thermally linked, magnetically independent, 2-in-1 type;

II) (Style A) High-field cos Θ, mechanically, thermally, and magnetically linked 2-in-1 type;

III) (Style D) High-field cos θ, 1-in-1 type with cold iron;

IV) (Style C*) Low-field superferric 1-in-1 type with cold iron;

V) (Style B) High-field cos θ, warm shielding iron 1-in-1 type.

Of the five basic styles, C and D were most strongly advocated by the proponents, and most of the discussion centered on these two styles.

The first day (August 25) of the MSAP meeting consisted of formal presentations by the Director of the CDG and the Chairman of the Technical Magnet Review Panel (TMRP) in the morning. Following were brief presentations by those asking to be heard on general issues having to do with magnet style choice. In the afternoon, each of the proponent groups made extended technical presentations describing their magnets and the status of development. The second day (August 26) was devoted to presentations by the CDG staff on issues of commissioning and operations, aperture estimates, and cost estimates. There was also adequate time for open discussion of the cost issues, variations in tunneling cost, and other issues during this period.

The Panel addressed written questions to the proponents and scheduled the full morning session of the following day (August 27) for the responses and further discussion with them. Throughout the meeting, a number of executive sessions were held, including an extended period (afternoon of August 27 and full day August 28) for further Panel discussion and report preparation.

Section II of this report contains the recommendation and comments of the Panel. Section III gives a supporting discussion of the R&D to date, the production costs, associated conventional construction costs, and questions dealing with accelerator physics and operations. More detail on the R&D evaluation is presented in Appendix F, Magnet Development Status. The Statement of the Industrial Consultants is given in Appendix G. Appendix H contains a submission by the Texas Accelerator Center (TAC) group at the meeting.

II. RECOMMENDATION

II-A. RESPONSE TO THE CHARGE (Appendix B)

The Panel considered all five proposed magnets. Magnets C and D, which were the principal foci of the proponents, were analyzed in most detail by the Panel. We first discuss the other three magnets. Magnet A, a 2-in-1 design, has magnetically coupled apertures. As pointed out to the Panel by the Report of the Task Force on Commissioning and Operations (SSC-SR-1005), it will be more difficult to commission and operate an accelerator built from such magnets. The Panel agrees and furthermore believes that these factors outweigh any apparent cost advantage of Style A with respect to the other styles. Magnet B is an early design by some of the proponents of magnet D; the latter is now preferred by them. It differs from D only in the detailed placement of iron flux return. In any case, magnets B and A share many of the mechanical and cryogenic features of magnet D. Magnet C* is the 1-in-1 version of magnet C and has most of the features inherent to C discussed below. The costs of the magnet-dependent systems for C* are higher than those for C.

The two principal magnets placed in competition, therefore, were C and D. The Panel is unanimous in recommending D as the design basis for an SSC dipole element. The hope of two years ago that the superferric magnet would provide a less complicated and less costly SSC has not become true. The Panel believes that there is a real possibility that an SSC based on superferric magnets would be more costly than currently estimated. On the other hand, the cos θ design has proceeded smoothly and met all expectations. For these and other reasons to be discussed, the Panel believes that the cost of an SSC based on cos θ magnets is predictable.

II-B. COMMENTS

In order to carry out a project in the most economical way, those approaches to the design of components having the least well-established techniques must be identified and studied. Research and development on the most viable approaches must be pursued to determine which will advance the project's performance goals with high confidence of success at least cost. As the R&D program proceeds, it is necessary to drop off the less promising approaches as rapidly as it can be reasonably established that their promise is not as great as that of the other contending approaches; otherwise, the R&D effort will be unduly expensive. Several approaches to the design of the superconducting dipole magnet for the SSC have been pursued for about two years now, and consensus among the researchers has narrowed the field of candidate designs to two, each representing one of the two main styles of construction, superferric and $\cos \theta$. After hearing presentations and arguments in favor of each of these styles, the Panel agrees that now is an appropriate time to choose between them.

The progress on the $\cos \theta$ style has shown it to be a well understood magnet with reliably predictable costs and production schedules. The reliability of the predictions rests on a large base of data developed in building and operating one large accelerator and developing models and prototypes for several others.

On the other hand, the work with the superferric style has shown it to be more complex than foreseen two years ago. As a result only models of one-meter length have been extensively tested so far. In the Panel's opinion, this style has not displayed the simplicity and ease of construction and operation it originally promised. Of course, if the superferric style held out the promise of substantial construction cost saving to outweigh the additional R&D costs required to develop it for production, it would be a strong candidate despite its less mature state of development. Although its proponents argued that this was the case, the Panel is convinced that, as cost studies done by the CDG suggest, the contrary is true. Use of the superferric style,in the Panel's opiniion, is likely to result in higher total project costs, exclusive of R&D.

In view of these findings, the Panel recommends that the choices between the two styles be made now and that the $\cos \theta$ style D be chosen.

III. DISCUSSION

Following is an evaluation of (A) Research and Development to date; (B) Production Costs; (C) Conventional Construction Costs; and (D) Accelerator Physics and Operations.

III-A. RESEARCH AND DEVELOPMENT

Status

Appendix F of this report outlines a brief history of the application of superconducting magnet technology to the synchrotron and to the storage ring. The central feature of this history is the extensive development beginning in 1974 of the Tevatron magnet and the construction and operation of the machine itself. In the last two years a number of promising new ideas for magnet styles applicable to a much larger machine have been developed and explored. These include the styles represented by the types A, B, and D based upon the cos θ winding, and types C and C* which employ the hybrid superferric style. Of these, types A and C seemed two years ago to be particularly promising approaches for an SSC.

The presentations heard by the Panel have amply described the profitable last two years of development of these early ideas. The Panel's conclusion is that the initial simplicity seen in the superferric style, as exemplified by magnet C, has not been borne out by the development that has been done, and that the seeming cost advantages of magnet A are compromised by operating problems and uncertainties. Instead, the Panel finds that the D style emerges as the one most suitable for the SSC.

R&D Base and Production Readiness

The much more extensive R&D base supporting the D magnet in comparison to that supporting the C magnet has important consequences for bringing the two types into production. This is discussed extensively in Appendix F. The data base and experience provide confidence in estimating costs for magnet D and allow a rapid and efficient response if parameters change or if engineering or production difficulties should arise. It is in this context that the Panel accepts the opinion of its industrial consultants, provided in Appendix G, as to the greater degree of production readiness of the type D magnet relative to the type C magnet.

Future R&D, Superferric Style

The evidence that the Panel has heard does not support the early hopes that the superferric magnet will be significantly simpler than the cos θ magnet. For instance, the accuracy of conductor placement needs to be similar in the two cases; in addition, the control of the field quality in the superferric magnet requires controlling the magnetic properties of the iron laminations at both low and high fields. There has been an evolution of the superferric designs in the last two years toward greater complexity. This evolution is reminiscent of the early days in the development of the cos θ magnets. The opinion formed by the Panel is that future R&D on the superferric magnet would result in growing complexity and higher rather than lower costs.

III-B. PRODUCTION COSTS

The CDG presented the Panel with estimated production costs for the various magnet types. In their words, "these costs assume that all primary technical components have been developed to a state of engineering design readiness and that a significant number of main ring production models have been produced and tested successfully." It is noted that both proponent groups accepted the CDG cost estimate per dipole unit. In the opinion of the Panel, the potential for cost growth for the C magnet is far larger than that for the D magnet; this trend is evidenced by the growth in estimated cost over the past year. (See Cost Comparisons for SSC Magnet Dependent Systems SSC-SR-1012.) In this regard, the Panel disagrees with the above assumption used by the CDG in arriving at contingency figures for the magnet C design. The present state of the magnet C design places it far behind the state of engineering design readiness of magnet D. This means that the contingency, which is quoted at about 21% for C, should be higher. This was also the opinion of the Panel's industrial consultants, as presented in Appendix G.

The Panel notes that exception was taken by the TAC group to the CDG magnet-related-systems cost estimates and required tunnel circumference for the C magnet. (See Appendix H.) They propose a 7% decrease in the magnet-dependent system costs due to an increased operating field and a 3.5% decrease in the tunnel cost due to a new shorter quadrupole design.

These changes in the dipole field and quadrupole design were introduced at the meeting; if accepted, they would decrease the circumference. Since these changes will likely result in an increase in individual magnet costs, the effect on the overall costs is presently unknown.

III-C. MAGNET DEPENDENT CONVENTIONAL CONSTRUCTION COSTS

According to the CDG data, the total magnet related costs will be 4% ($80 million) higher for the C style magnet than the D style with weighted average tunnel cost of $930 per linear foot. In our opinion, the tunneling costs which were used in arriving at these unit costs were realistic in view of the known costs of recent accelerator tunnels for projects constructed in the USA. These figures were also confirmed by the investigation of experienced A/E firms.

The Panel feels that the figure of $930 per linear foot is a sound one; however, the TAC group argued (see Appendix H) that this figure should be lower on the grounds of the assumption of far more favorable tunneling conditions and labor rates than those used by the CDG. The Panel notes that even if the unit costs were lower by as much as 22%, the total magnet-related costs of the C style and the D style would only break even. The Panel feels that the assumption of unit tunnel costs lower than those used by the CDG would be imprudent.

The above remarks apply to the comparisons presented of the C and D styles. The disparity in total magnet dependent system costs is far greater in favor of the D style when it is compared to the C* style.

III-D. ACCELERATOR PHYSICS AND OPERATIONS

The selection of a magnet style must take into account that the SSC is likely to be the only machine for high-energy particle physics in this energy range in the 1990's. Therefore, its design, construction, and operation must aim at obtaining a machine with a high level of reliability. As far as accelerator physics and operational questions are concerned, this aim implies that (i) adequate aperture and field quality for the beam are available under all anticipated operating conditions; (ii) collective phenomena do not limit the nominal performance; and (iii) the magnet style does not cause substantial operational difficulties. The Panel prefers the magnet style D in all these areas. Our reasoning is summarized below.

The Aperture Task Force has made assessments of the adequacy of the apertures of magnet styles C and D. The method used was to consider the guide field to be linear (to have no systematic higher order multipoles) except for perturbing multipole fields appearing in each magnet randomly at the levels of the rms errors of the multipole coefficients for the two styles. By tracking particles in such a guide field, a linear aperture was established for each style, and then further the dynamic aperture was shown in each case to be larger than the linear aperture. The details of the method are given in SSC-SR-1013. The Aperture Task Force concludes that either style C or style D magnets are satisfactory; however, for large amplitudes the orbits are somewhat better behaved in style D.

Among the collective effects, the fast head-tail instability has the lowest beam current threshold (cf. SSC-SR-1013). In order to put the threshold at the nominal current, the momentum spread must be a factor of three higher in a machine built with 3 Tesla magnets than in a machine built with 6 Tesla magnets. This momentum spread is not much smaller than the momentum aperture shown in Fig. 16 of SSC-SR-1013. Given the uncertainties in the theory of the fast head-tail instability, and in the calculation of the impedances, the Panel considers that an SSC built with style D magnets is sure to meet its performance goals than an accelerator utilizing style C magnets.

The Task Force on SSC Commissioning and Operations has considered the effects of the various magnet styles. The Panel concurs with their conclusion that there is a preference for magnet styles with cryogenically and magnetically separated rings. Magnet style D satisfies this condition, while style C does not. Magnet style C* is both cryogenically and magnetically separated but its cost is higher than any of the other styles, and it has not been engineered to the same level as style C.

The total number of stored beam particles, the stored energy in the beam which has to be absorbed by the beam dump, and the pulse length of the beam-abort kicker magnets are all proportional to the circumference of the SSC which is almost a factor of two larger for style C than for style D. The Task Force on SSC Commissioning and Operations states that the concomitant problems arising with magnet style C can all be solved. However, it is obvious that the associated cost is lower for a ring of smaller circumference.

As a final point it should be noted that the Report of the Task Force on SSC Commissioning and Operations (SSC-SR-1005) concluded that there could be additional operating costs and additional staff required for the larger ring, and the Panel concurs.

APPENDIX A. PARTICIPANTS LIST

MAGNET SELECTION ADVISORY PANEL MEETING

August 25-28, 1985

MAGNET SELECTION ADVISORY PANEL

Frank Sciulli, Chairman - Columbia U.
Eberhard Keil - CERN
Neal F. Lane - U. of Colorado
Michael S. McAshan - Stanford U.
John R. Rees - SLAC
E. Parke Rohrer - Rohrer Associates Inc.
Alvin V. Tollestrup - FNAL
Bjorn Wiik - DESY

CONSULTANTS TO THE PANEL

Ray F. Beuligmann, VP Research and
Engineering - General Dynamics Convair Division

Cord-Henrich Oustmann, Group Leader
for Marketing and Development of
Superconducting Magnets - BBC-Brown,
Boveri & Cie, Mannheim

John K. Hulm, Director of Corporate
Research - Westinghouse R&D Center

BROOKHAVEN NATIONAL LABORATORY

Carl L. Goodzeit
Arthur F. Greene
Robert I. Louttit
Paul J. Reardon
Erich H. Willen

SSC/CENTRAL DESIGN GROUP

Alex Chao
Tom Elioff
J.David Jackson
Peter J. Limon
James R. Sanford
Clyde Taylor
Timothy Toohig
Maury Tigner
Ronald B. Yourd

FERMI NATIONAL ACCELERATOR LABORATORY

D. Edwards
Helen T. Edwards
H.E. Fisk (Mon.)
Leon M. Lederman (Sun.)
Richard A. Lundy
Paul M. Mantsch

LAWRENCE BERKELEY LABORATORY

Klaus H. Berkner
Jay N. Marx
Ronald Scanlan
David A. Shirley
(Clyde E. Taylor)

TEXAS ACCELERATOR CENTER

F. Russell Huson
E. R. Kimmy - General Dynamics (Sun.)
Peter M. McIntyre
Waldo MacKay
Edward J.N. Wilson - CERN

SSC BOARD OF OVERSEERS

Edward Knapp - Los Alamos
Chris Quigg - FNAL
George H. Trilling - UCB

DEPARTMENT OF ENERGY

Robert E. Diebold
L. Edward Temple

APPENDIX B. CHARGE TO THE SSC BASIC MAGNET TYPE SELECTION ADVISORY PANEL

A number of Basic Magnet Types have been considered for possible SSC service. They include mechanically linked dual aperture magnets which may or may not be thermally or magnetically linked (2-in-1) and mechanically, magnetically and thermally independent single aperture magnets (1-in-1). Both high field (6T or more) and low field (about 3T) versions of these types have been studied and developed to a greater or lesser extent. After considerable study of the many possible combinations, five have emerged as the most likely to provide economical and reliable options of the SSC. These five are: 1. a low field, mechanically and thermally linked, magnetically independent 2-in-1 type; II. a high field, mechanically, thermally and magnetically linked 2-in-1 type; III. a high field 1-in-1 type with cold iron; IV. a low field 1-in-1 type; V. a high field, warm iron 1-in-1 type.

During the last quarter of Fiscal Year 1985, one of these Basic Magnet Types will be selected for final prototype development by the Director of the Central Design Group. In aid of this selection the Advisory Panel will submit a report to the Director containing the Panel's recommendation in the form of an ordered list of these five Basic Magnet Styles. The rationale for this recommendation should be given in detail. If no clear choice emerges this should be clearly stated and justified.

In making its recommendation the Advisory Panel will be guided by the Criteria set forth below, using technical materials supplied by the CDG and such other technical inputs as it may solicit at its discretion.

The report of the Advisory Panel is due by August 20, 1985, or before if possible.

Criteria

In its deliberations the Panel will consider the SSC to be a hadron collider designed ultimately to achieve 20 TeV per beam at a luminosity of $10^{33}cm^{-2}sec^{-1}$.

In rendering its judgment the Advisory Panel should consider the general implications of low field and high field and 1-in-1 and 2-in-1 features as well as details of proposed mechanical, thermal and magnetic designs. Both system features and characteristics of the magnets considered as individual components need to be taken into account. While the dipoles are the major cost component of the magnet system, the quadrupoles and various correctors inherent to the various Basic Magnet Types must receive due consideration.

The Criteria to be used in making an overall recommendation are

1. Relative capital cost of an SSC facility employing a particular Basic Magnet Design.
2. Workability of the Basic Designs presented.
3. Complexity of the overall magnet system inherent to the particular Basic Design.
4. Operational complexity of an SSC employing the particular Basic Design.
5. Relative flexibility of an SSC design employing the particular Basic Design.
6. Likely impact of the Basic Magnet Design on the SSC construction schedule.
7. R&D time and effort needed to develop the Basic Design.
8. Accelerator Physics considerations.
9. Other considerations deemed appropriate by the Advisory Panel.

Comments on the Criteria

1. Cost figures will be developed by the CDG with input from the SSC R&D participants and from independent commercial firms experienced in manufacturing superconducting magnets. In calculating the overall SSC facility cost, the conventional construction costs developed by the CDG and its A/E consultant will be used. The Reference Designs Study will be a primary reference. In computing magnet costs, the CDG will select the aperture to be used with each Basic Magnet Type based on accelerator physics considerations and the best information available on the likely field errors for each Basic Magnet Type.

2. Workability or practicality refers to the manufacturability and potential reliability of a particular design, taking into account needed tolerances, material specifications and assembly procedures. Model tests by the developers will provide concrete evidence in this area.

5. Relative flexibility is with regard to: a) possibilities for staging the SSC to speed up first physics use while reducing spending rates if necessary; b) operations such as injection, beam adjustments during collisions, repair of magnets; c) concommitant site restrictions.

6. Particular impacts might be lengthened construction time for larger circumference, needs for special portals or on-site factor facilities for particular magnet designs, duration of manufacturing time for various magnets.

7. Accelerator Physics issues would have to do with inherent properties of low and high field rings and coupled or uncoupled beam channels. One would expect vacuum chamber impedance, surveying, magnet shuffling, radiation protection and other considerations to play a role.

Information to be Supplied by the CDG to the Advisory Panel

1. Report of the CDG Cost Estimating Task Force.
2. Report of the Task Force on Operations and Commissioning.
3. Report of the Aperture Task Force.
4. Drawings, specifications and model test results, where available, representing the current state of development of each of the Basic Magnet types.
5. Report of the Technical Magnet Review Panel.

APPENDIX C. LIST OF DOCUMENTS SENT TO MSAP PRIOR TO MEETING

(mailed August 16, 1985)

1. Report of Cost Comparisons for SSC Magnet-Dependent Systems, SSC-SR-1012, (August 15, 1985)
2. SSC Aperture Estimate for Cost Comparisons, SSC-SR-1013, (August 9, 1985)
3. Recent Magnet Test Data and Information From BNL (August 2, 1985)
4. Recent Magnet Test Data and Information From FNAL (August 5, 1985)
5. Recent Magnet Test Data and Information from TAC (August 15, 1985)

(mailed August 5, 1985)

6. Report of Technical Magnet Review Panel, SSC-SR-1010, (July 25, 1985) (and cover letter of Chairman TMRP)
7. SSC Interim Report, SSC-SR-1011, (June 1985)
8. Vol. 1 Reference Designs Study Report (May 8, 1984)
9. Agenda for August 25 meeting

(mailed July 8, 1985)

10. Report of Task Force on SSC Commissioning and Operations, SSC-SR-1005, (July 1, 1985)

APPENDIX D. SSC MAGNET SELECTION ADVISORY PANEL MEETINGS BEGINNING 25 AUGUST 1985

Sessions are in the Cockpit, URA Design Center, Lawrence Berkeley Laboratory, 4th Floor, Building 90. Space limitations require that attendance be restricted to invited participants -- panel members, consultants, presenters, selected CDG personnel, members of the SSC Board of Overseers, DOE program officer.

Agenda

Sunday, 25 August

9:00-10:00 Executive Session (F.J. Sciulli in charge, Panel and Consultants only)

- assignments, discussion

10:00-10:45 Overview (M. Tigner)

- introduction of participants
- CDG responsibilities
- R&D program
- selection process
- charge to the Panel

0:45-11:00 Break

1:00-12:00 Report of the Technical Magnet Review Panel (A. Tollestrup)

- charge to TMRP
- description of magnets
- report of TMRP

:00-12:30 General comments and remarks (short presentations, to be arranged with Chairman Sciulli: D. Shirley, L. Lederman, P. McIntyre)

:45-1:30 Working lunch and continuation of "General comments and remarks", if needed

Afternoon Session: Presentation of Candidate Magnets, with emphasis on progress in July and August

30-3:00 Superferric magnets, types C and C' (F.R. Huson, E.J.N. Wilson, E.R. Kimmy, W. McKay)

00-3:30 Cosine θ magnets, types A', B, D, part 1 (R. Lundy, P.J. Reardon, R. Scanlon)

0-3:45 Break

5-5:15 Cosine θ magnets, types A', B, D, part 2

-5:45 Open period for discussion

Monday, 26 August

Morning Session: CDG Presentations

8:30-9:15 Report of the Commissioning and Operations Task Force (P.J. Limon)

9:15-9:45 Aperture Estimates (A. Chao)

9:45-10:15 Cost Comparisons 1: Overall Scheme and Rollup (T. Elioff)

10:15-10:30 Break

10:30-11:15 Cost Comparisons 2: Conventional Systems (J.R. Sanford)

11:15-11:45 Cost Comparisons 3: Magnets (R.B. Yourd)

11:45-12:15 Concluding Remarks (M. Tigner)

12:15-1:30 Lunch Break

Afternoon Session: General Discussion and Executive Session

1:30-4:45 Discussion of all relevant issues (F.J. Sciulli presiding)

(15 minute break somewhere)

4:45-5:45 Executive Session (Panel and Consultants only)

6:00-8:00 Social hour (starting earlier for some)

Tuesday, 27 August **General Discussion and Executive Session**

8:00-9:00 Executive Session (Panel and Consultants only)

9:00-12:00 Responses by Proponents and Discussion

12:00-6:00 Executive Session (Panel and Consultants only)

Presentation of summaries by panel members, discussion, outlining of report, writing assignments, etc.

Wednesday, 28 August (Panel members and consultants only)
Further deliberations, writing of the report

JDJ:dm
8/16/85

APPENDIX E. ADDITIONAL DOCUMENTS PROVIDED TO PANEL AT TIME OF MEETING

1. "Overview: Presentation to the SSC Magnet Selection Advisory Panel" (M. Tigner)
2. Material on Technical Magnet Review Panel (A. Tollestrup)
3. Copies of Transparencies and other material used in TAC Presentation (R. Huson)
4. "Effects Which Lead to Field Errors in Iron Magnets" (E. Wilson)
5. "Texas Accelerator Center/General Dynamics Contract" (M. Kimmy)
6. Material on Errors in Multipoles in TAC Magnets (W. McKay)
7. "BNL, FNAL, LBL Present Design 'D' Cold Iron Cos θ Uncoupled: 1-in-1" (P. J. Reardon)
8. Material on Cos θ History (R. A. Lundy)
9. "Superconducting Materials for the SSC" (R. Scanlon)
10. "Report of Task Force on SSC Commissioning and Operations: Presentation to MSAP" (P. Limon)
11. "Aperture Estimates: Presentation to MSAP" (A. W. Chao)
12. "Cost Comparisons for SSC Magnet Dependent Systems: Overall Scheme and Rollup: Presentation to MSAP" (T. Elioff)
13. "Cost Comparisons for SSC Magnet Dependent Systems: Conventional Systems: Presentation to SSC/MSAP" (J. R. Sanford)

4. "Cost Comparisons for SSC Magnet Dependent Systems: Magnets: Presentation to SSC/MSAP" (R. B. Yourd)

5. "Peak Operating Field for Dipole Magnets" (C. Taylor)

. Answers to Written Questions Submitted to Proponents by SSC/MSAP

. Additional Materials Related to TAC Presentation · Aug. 27 Memo to F. Sciulli from F. R. Huson and P. M. McIntyre; "TAC SSC Magnet Selection Position Statement", Aug. 14; and Aug. 19 Memo to P. Reardon from P. Wanderer and Erich Willen on "Review of TAC Magnetic Field Measurements"

APPENDIX F. MAGNET DEVELOPMENT STATUS

Cos Θ Style

The cross section of a collared coil assembly for a cos Θ magnet is shown in Fig. 1(a), and the complete cross section for style D is given in 1(b). The field shape is controlled by the angles subtended by the various blocks of conductor and wedges. The many geometrical variables available to the coil designer allow control of the systematic even harmonics, b_n, up through n = 10. The collars, formed from precision stampings, provide the basis for accurate control of the conductor position (about 25μm) and furnish the support for withstanding the large forces present in a high field magnet. The collared coil subassembly has many advantages during production in that it can be immediately warm tested after fabrication for field quality. Such testing gives an overall monitor of the dimensional accuracy of the conductors, insulation, and collars prior to assembly into the cryostat.

The cos Θ coil concept is being used in all superconducting accelerators that are either operating or under construction and has had a long history of relevant R&D. The following table indicates this in some detail:

Institution	Machine/R&D Program
FNAL	Tevatron, R&D on SSC
DESY	HERA
Serpukhov	UNK
BNL	RHIC R&D CBA R&D SSC R&D
LBL	SSC R&D CBA R&D ESCAR
Saclay	HERA R&D Quadrupoles UNK R&D Dipoles
KEK	TRISTAN ep option R&D

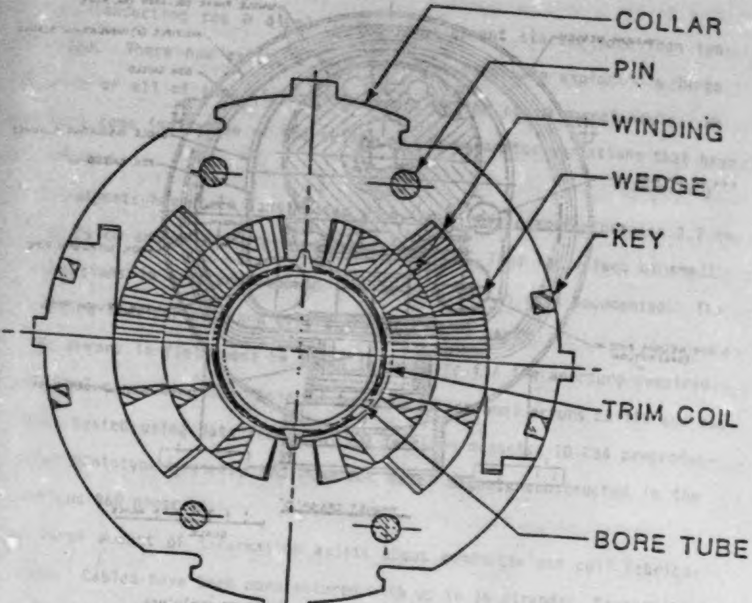
COLLAR
PIN
WINDING
WEDGE
KEY
TRIM COIL
BORE TUBE

Fig. 1(a). Cos θ style collared coil.

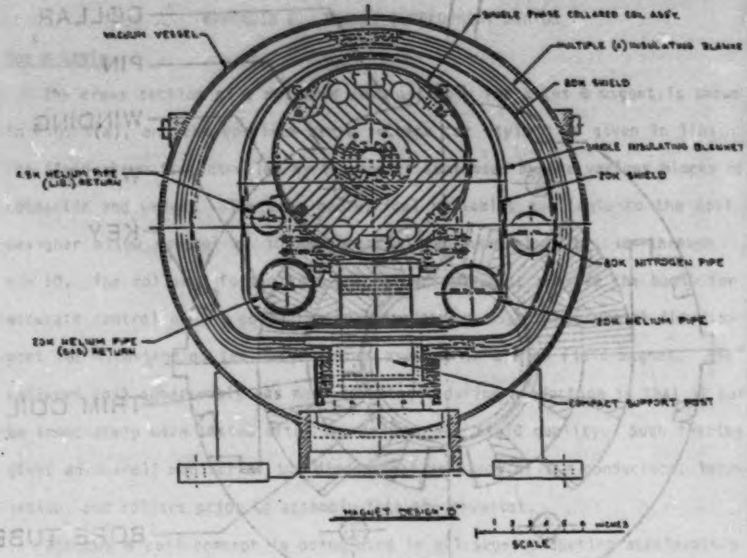
SINGLE PHASE COLLARED COIL ASS'Y.
VACUUM VESSEL
MULTIPLE (5) INSULATING BLANKET
80K SHIELD
SINGLE INSULATING BLANKET
4.5K HELIUM PIPE (LIQ.) RETURN
20K SHIELD
80K NITROGEN PIPE
20K HELIUM PIPE
20K HELIUM PIPE (GAS) RETURN
COMPACT SUPPORT POST
MAGNET DESIGN 'D'
1 2 3 4 5 6 INCHES
SCALE

Fig. 1(b). Cos θ completed cryostat and vacuum enclosure.

Superconducting cos θ dipole magnet development started more than ten years ago. There now exists a very extensive data base exploring a large variation of all of the relevant parameters of the cos θ magnet style. We give here some indication of the extent of the parameter variations that have been studied.

1. The magnets have been constructed with inner bore diameter between 3.2 cm and 25 cm and peak fields between 4T and 8T. Thus the effect of small variations in aperture, should they be desired, is well documented. The scaling laws for cost and errors are on a sound basis.
2. The errors in field must be known in order to fix the aperture required. A model connecting the field errors with dimensional errors exists and has been tested using data from over 800 Tevatron magnets, 10 CBA preproduction prototype magnets, and numerous model magnets constructed in the various R&D programs.
3. A large amount of information exists about conductor and coil fabrication. Cables have been manufactured with up to 36 strands. Keystoning is well understood. Filament sizes between 2μm and 20μm have been studied. Kapton insulation with and without epoxy loaded fiberglass has been studied. The elastic properties of the coil package, creep under preload, high voltage integrity, etc., have all been studied and documented.

Data on the cryostat and the magnet support system exist from the Tevatron construction, HERA and CBA studies, and the SSC model cryostat studies.

A considerable amount of system related information is available from the Tevatron operation. The Tevatron furnishes a test bed and provides extensive data relating actual machine performance to that predicted from measurements in the cos θ style magnet.

As the engineering details of the design become finalized, it may be possible to use a passive quench protection system, as proposed for CBA. However, active quench protection as used at the Tevatron provides a well tested back-up scheme. No new technology or component development is required since the conductor current is only 5000A and is in the range of presently available SCR's and diodes.

An area of engineering R&D under active investigation is the control of the systematic sextupole and decapole terms. These terms arise from saturation of the iron and from persistent currents in the superconducting filaments. The sextupole effect from the iron is small and easily corrected since the nonmagnetic collars keep the iron boundary at a rather large radius. The persistent currents generate sextupole and decapole terms which are large at injection and rapidly damp out as the field increases. Three tested techniques are available for controlling these terms:

1. The filaments of superconductor may be made small enough so the effect is not important.
2. The fields may be cancelled with a distributed correction coil as was demonstrated for the CBA magnets.
3. The fields may be cancelled using passive superconductor arranged in such a way that the field components generated by persistent currents in its filaments cancel those of the coil conductors.

The question of which method to use will be determined by cost, ease of fabrication, and reliability of operation.

Magnetic measurement data for this style of magnet are extensive for the central field as well as for the field integrated through complete magnets 4.5 to 6 meters long. Measurement techniques are being developed at BNL to allow measurement of 16 meter dipoles or longer when they become available. The presently available measurements for the D style were performed on 4.5 meter models.

The involvement of industry with the $\cos\theta$ style magnet has already begun. Brown Boveri has been heavily involved in the prototype development of the HERA dipoles. The 416 nine-meter HERA dipoles and 208 quadrupoles will be built in industry. Half of these will be constructed in German industry under competitive bidding. The other half will be built under contract with an Italian consortium. The first industrially produced magnets are due by the middle of 1986 with completion of delivery scheduled for the end of 1988.

In addition, in this country there has been a very close collaboration between the University of Wisconsin, the National Laboratories, and industry in the development of superconductor with high J_c and small filament size.

Finally, the CDG has relied heavily on industrial assistance for help in developing cryostat requirements, manufacturing plans and realistic cost estimates for the magnet styles being studied for potential use in the SSC.

Superferric Style

The cross section of the superferric style magnet, type C, is shown in Fig. 2(a) and a close-up of the magnet coil and yoke in Fig. 2(b). Type C* is a variation that consists of a single aperture magnet in a single cryostat, and this type magnet has been used in some of the model tests described below.

The superferric magnet resembles a normal magnet from injection at 0.3 T to about 2 T. However, there are two rather unique aspects of the design in this "low" field region when compared with iron magnets used for accelerators. The first arises from the iron shunts which are shown in Fig. 2(b) at the edges of the gap which saturate at a very low field. They aid in reducing the field at the conductor at high field, in the assembly of the magnet, and in controlling the field shape at low field. The second is the rather high aspect ratio of gap height to width of about 0.8 compared to a normal iron

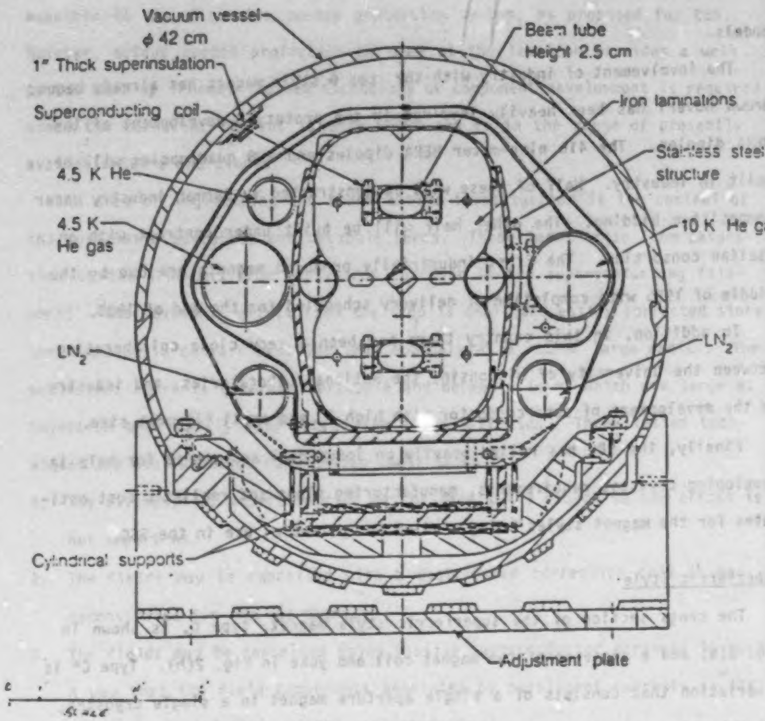
Vacuum vessel
ϕ 42 cm
1" Thick superinsulation
Superconducting coil
4.5 K He
4.5 K He gas
LN$_2$
Cylindrical supports
Beam tube Height 2.5 cm
Iron laminations
Stainless steel structure
10 K He gas
LN$_2$
Adjustment plate
Scale

Fig. 2(a). Superferric C style cryostat and vacuum enclosure.

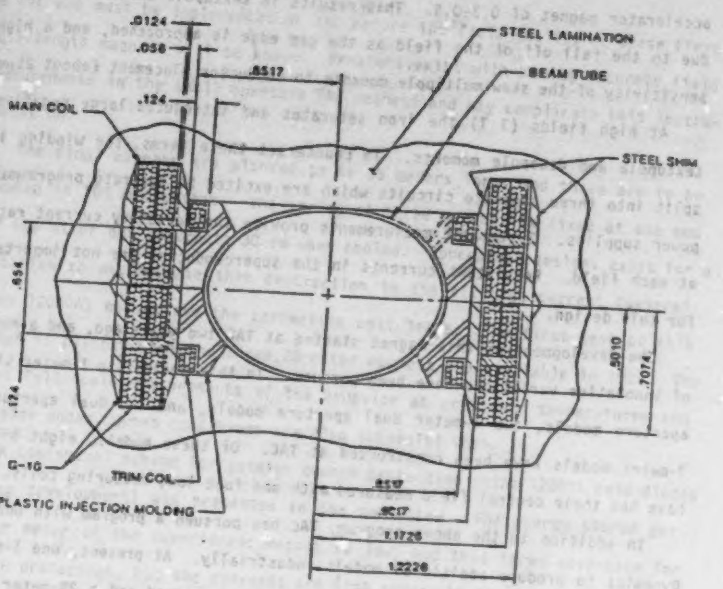
.0124
.056
.124
.8517
STEEL LAMINATION
BEAM TUBE
MAIN COIL
STEEL SHIM
.934
.124
.5010
.7074
G-10
TRIM COIL
PLASTIC INJECTION MOLDING
.8517
.9C17
1.1726
1.2226

Fig. 2(b). Superferric superconductor-beam tube assembly.

accelerator magnet of 0.3-0.5. This results in sextupole and decapole terms due to the fall off of the field as the gap edge is approached, and a high sensitivity of the skew multipole moments to conductor placement (about 25μm).

At high fields (3 T) the iron saturates and introduces large negative sextupole and decapole moments. To counteract these terms, the winding is split into three separate circuits which are excited by separate programmable power supplies. Systematic measurements provide the necessary current ratios at each field. Persistent currents in the superconductor are not important for this design.

The development of this magnet started at TAC two years ago, and a number of innovative variations have been pursued. In this period six 1-meter single aperture models, two 1-meter dual aperture models, and two dual aperture 7-meter models have been constructed at TAC. Of these models, eight bores have had their central field measured with one foot long measuring coils.

In addition to the above program, TAC has pursued a program with General Dynamics to produce additional models industrially. At present, one 1-meter single aperture magnet has been fabricated and measured and a 28-meter two aperture magnet with the first complete cryogenic system will be delivered for test in October 1985. Two more 28-meter magnets are planned for delivery by the end of the calendar year.

Considerable work has been done to improve computer codes for predicting the behavior of the superferric magnets. This work has resulted in a model relating magnet field errors to the properties of iron and dimensional tolerances. The data base from completed magnets to assure that the required accuracies can be achieved through quality control in a production environment does not exist.

The technology for measuring the fields in long magnets is being developed at BNL and must be implemented at TAC before the field quality of these first full-length magnets will be known. Problems exist with making accurate field measurements in the small aperture TAC magnets and may complicate this instrumentation.

The final magnets are planned to be 35 meters long, and three are to be mounted in 105 m cryostat. The string of three magnets is fixed at one end and the other end contracts 30 cm when cooled. Conceptual designs exist for a mechanism to accommodate this contraction in the six high current (several carry 12000A) busses and the correction coil leads. The first test of this design is planned when the three 28-meter magnets are available in 1986. The first full-scale measurements of the behavior at cryogenic temperatures and behavior under quench conditions are also scheduled then.

A conceptual scheme for passive quench protection using 12000A cold diodes (under development) was presented to the committee. The energy stored per linear meter of the superferric magnet is low, and this is an advantage for quench protection, but the currents are high enough to require that new diodes be developed or that the problem of current sharing between two parallel diodes be solved.

The stress analysis of the magnet and cryostat was discussed. TAC indicated that a contract for a complete analysis has been signed with General Dynamics, and results will be available in six months.

APPENDIX G. STATEMENT OF THE INDUSTRIAL CONSULTANTS

As industrial consultants to the Magnet Selection Advisory Panel, we have been asked to comment on those factors relating to all aspects of industrial production of the SSC magnets, with specific reference to designs C and D. We perceive the following major factors to be relevant to support the MSAP deliberations.

R&D Phase

In our definition, the Research and Development phase is finished when the following are completed: material specifications, component detail design and testing, analyses, tool design, manufacturing processes, and prototype testing. We are in unanimous agreement that on this definition, the cos Θ style magnet is at a more advanced state of development than the superferric style magnet, for the following reasons.

The cos Θ style has an extensive base of R&D, testing, production and operating knowledge. More than 1000 units have been incorporated in a large machine which is in successful operation. Extensive R&D has continued to refine the cos Θ style design in the past several years. We believe that the cos Θ design is a mature technology.

A very limited data base exists for the superferric style magnet. The first long superferric magnet will be tested in the first quarter of FY 1986. It is our conclusion that the superferric style magnet technology is not mature. There are more unknowns in the superferric style design. This should be interpreted as higher risk and longer R&D schedule needed for the superferric style.

It is our judgment that the superferric style will need at least two years more R&D development time than the cos Θ style design.

Production Phase

We conclude that either style magnet design in its present state of development, can be produced in industry and achieve the production rates specified in the CDG plan. Manufacturing studies have already been performed by General Dynamics, Westinghouse and Brown Boveri. General Dynamics has assembled one 1 m magnet and one 28 m magnet of the superferric style. Brown Boveri has already built eight magnets of the $\cos \theta$ style, four for the Brookhaven RHIC and four for HERA at DESY. Thus, we conclude that from the point of view of producibility there is no reason to chose one style over the other.

It is our view that the production rate required by the CDG plan can be uccessfully met, provided that the following involvement with industry is chieved:

1. The current level of industrial involvement should be increased in der to meet the present CDG construction schedules. Industry should have experience of doing the production plan and assisting the magnet-elopment laboratories in the detail design, fabrication, and testing of totype magnets prior to the preproduction phase.

2. Industry must have the experience of doing the tool design, tool fabri-on, and magnet fabrication of the preproduction magnets in their own shops r to production contract awards. The deliveries of production magnets per DG plan can start 12 months after production contract award.

and Schedules

believe that the CDG cost estimates are sufficiently accurate to sup-he decision of selecting the magnet style for the SSC at this time. is a higher degree of cost and schedule uncertainty with the superferric agnet. The contingency factors applied for the two magnet styles by are relatively close. We feel that the cost contingency factor for the superferric style should be greater than stated, due to the higher degree of uncertainty both in cost and development schedule.

As an example of the higher uncertainty of production costs for style C, we note that the cos θ style coil can be warm tested for field quality prior to insertion into the yoke. The superferric style cannot be warm tested in a similar manner due to the non-linear field dependency for the iron. Therefore, the quality of superferric windings can only be verified in a final cryogenic test. This type of in-process test cited as possible for the cos θ magnet is very important in reducing costs in production. We draw attention to this difference as support for the argument of having a higher cost contingency factor for the superferric style design.

C.H. Dustmann, Brown Boveri
R.F. Beuligmann, General Dynamics
J.K. Hulm, Westinghouse

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APPENDIX H

August 27, 1985

To: F. Sciulli, Chairman, Magnet Selection Advisory Panel

From: F.R. Huson and P. M. McIntyre, Texas Accelerator Center F. Huson

Subject: Protest of specific items presented in the MSAP hearing

After consideration of the material presented to MSAP for their consideration, we must specifically contest the following items:

1. During all meetings of the Magnet Technical Review Panel, the field values for the Designs C and D were taken as 3T and 6T, respectively, even assuming improved superconductor. Any incremental capability for higher field was treated as a safety margin.

   CDG used 6.4T for Design D, informing us two days in advance. We request, correspondingly, that Design C be treated as a 3.2T field design. We believe that all aspects of field quality, quench behavior, and mechanical/electrical design are consistent with this margin of increase. We will investigate these aspects in detail during the coming weeks. All magnet systems and tunnel systems for Design C then should be reduced by 7%.

2. We were told yesterday that a circumference of 172 km for Design C was adopted since we did not have a quadrupole design. We presented a quad design in the meeting that is consistent with the 166 km circumference that has been used in all calculations to date. We request that all quadrupole costs be reduced appropriately, and tunnel costs be reduced by 166/172.

3. We presented data showing actual tunnel costs being achieved today in 3 tunnel projects near Austin, Texas. Using a tunnel cost-estimating computer code (COSTUN) which benchmarks these costs correctly, we presented estimates of $500/ft for a 10 ft. diameter, 100 mile circumference tunnel at four potential SSC sites in Texas. We contend that the $930/ft cost used by CDG assumes that no serious effort will be made to choose an SSC site that minimizes tunnel cost. We request that a $700/ft tunnel cost be used. We emphasize that the low tunnel costs demonstrated in Texas are not Texas-specific, but rather result from choice of good site geology.

4. The CDG cryogenics estimate included a warm gas return heater that is not needed in Design C.

The effect on magnet choice-dependent project cost of the above items is

1.	6.7% reduction of all items except other technical	$101M
2.	3.5% reduction in tunnel systems	40M
3.	$230/ft reduction in tunnel cost	186M
4.	$8M reduction in cryogenic cost + contingency	10M
		$337M

The resulting Design C total cost for magnet-dependent costs is $1,846M, to be compared with $2,100M for Design D.

Erratum: the Design D cost should be reduced by .6 × 186M = $114M due to reduced tunnel cost assumption.
net cost = 1.984M for Design D.

FRH-PMM:dm

Erratum: The Design D cost should be reduced by .6 x 186M = $114M due to reduced tunnel cost assumption. Net cost = $1.984M for Design D.

APPENDIX 5

SSC-SR-1005
01 July 1985

REPORT
OF THE TASK FORCE
ON SSC COMMISSIONING AND OPERATIONS

Superconducting Supercollider Central Design Group
c/o Lawrence Berkeley Laboratory
Mail Stop 90-4040
Berkeley, California 94720

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1. INTRODUCTION

In 1985 January a Taskforce was organized to study the impact of magnet design on the commissioning and operation of the SSC. The results of the study, in the form of this Report, are intended as one of several sources of input for the Magnet Type Selection Committee. Other major input will come from the Magnet Taskforce, the Test String Taskforce, the Cost Estimating Taskforce, and other study groups. All of these efforts will culminate in a magnet type selection, after which concentrated R&D on the selected magnet can commence. The interplay of the Commissioning and Operations Taskforce with the rest of the Central Design Group effort during this period is shown schematically in Fig. 1-1.

The study began with a one-week workshop, held on the UC Berkeley campus in 1985 January 14-18. An interim report of the Taskforce, based on the results of the Workshop, was published on 1985 January 28 (SSC-05). The agenda of the Workshop is included as Appendix 2 of this Report.

With very few exceptions, the work of the Taskforce was carried out by the participants in the Workshop, both during the workshop and in the subsequent weeks. These participants are listed in Appendix 1. This Report is the collective effort of that group, whose very substantial contribution of time, effort, and thought is gratefully acknowledged.

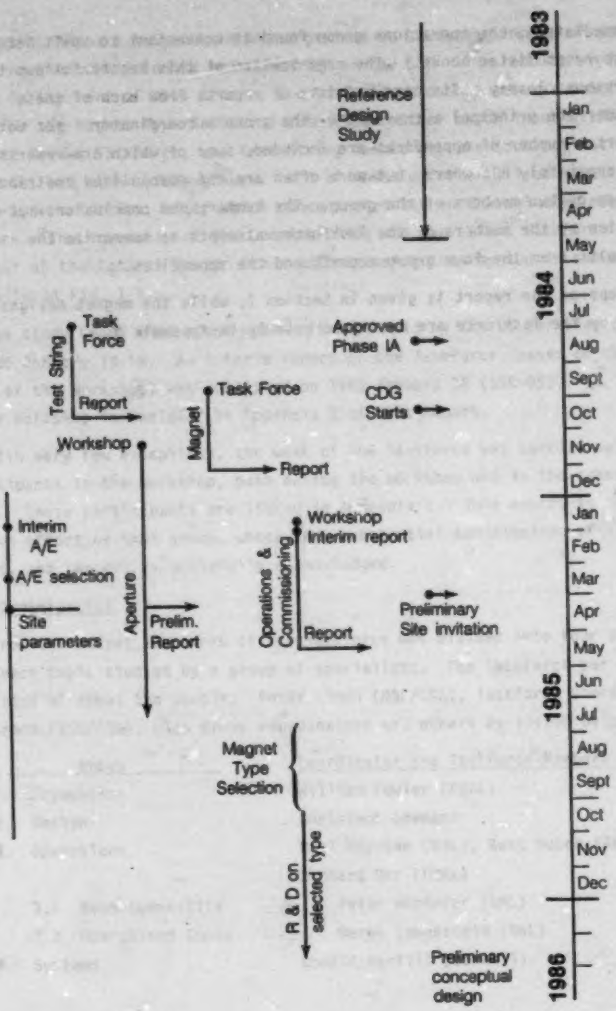
1.1 Organization

From the outset, the work of the Taskforce was divided into four topics, with each topic studied by a group of specialists. The Taskforce per se consisted of about ten people: Peter Limon (SSC/CDG), Taskforce Coordinator, Don Groom (SSC/CDG), plus group coordinators and others as listed below:

Group	Coordinator and Taskforce Members
1. Cryogenics	William Fowler (FNAL)
2. Design	Christoph Leemann
3. Operations	Paul Reardon (BNL), Russ Huson (TAC), Richard Orr (FNAL)
3.1 Beam Gymnastics	Peter Wanderer (BNL)
3.2 Operations Costs	Derek Lowenstein (BNL)
4. Systems	Donald Hartill (Cornell)

(Almost immediately, the operations group found it convenient to split into the two subgroups listed above.) The organization of this Report follows that of the workshop closely. Its core consists of reports from each of these groups, under the principal authorship of the group's coordinator. For each group report a number of appendices are included, some of which are reports published separately elsewhere, but more often are the specialized contributions of one or two members of the group. The summary and conclusions section, written by the members of the Taskforce, attempts to summarize the cogent results from the four group reports and the appendices.

The scope of the report is given in Section 2, while the magnet designs considered by the Taskforce are described briefly in Appendix 3.


1983
1984
1985
1986
Jan
Feb
Mar
Apr
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Jun
Jul
Aug
Sept
Oct
Nov
Dec
Reference Design Study
Approved Phase IA
CDG Starts
Test String
Task Force
Report
Magnet
Task Force
Report
Workshop
Aperture
Prelim. Report
Interim A/E
A/E selection
Site parameters
Operations & Commissioning
Workshop
Interim report
Report
Preliminary Site invitation
Magnet Type Selection
R & D on selected type
Preliminary conceptual design

Fig. 1-1. Phase I schedule for the SSC.

2. SCOPE OF THIS REPORT

In its narrowest form, the Taskforce was to consider the commissioning and operational characteristics of a 20 TeV proton-proton collider system based on the four basic magnet designs presently under consideration. The first three were somewhat evolved from those of the Reference Design. The fourth ('Type D') is essentially a marriage of Reference Designs A and B---a cold iron, stainless steel collared, 6T one-in-one magnet. These magnets are briefly described in Appendix 3.

In trying to decouple thinking about such parameters as field strength and cryogenic coupling with specific designs, the Taskforce attempted to consider more generic magnet styles. These styles were:

1. One-in-one designs, with the magnets of each ring in the collider in separate cryostats.
2. Two-in-one designs, with the magnets of each ring in the same cryostat, with common cryogenic piping. The two-in-one magnets could be of two distinct types:
   2(a). Magnetically coupled.
   2(b). Magnetically uncoupled, or at most weakly coupled.
3. For all of the above types, the Task Force considered both high field (6T) and low field (3T) designs.

In spite of the broadened discussion, no particular new advantages appeared, and the Taskforce spent most of its time discussing the existing magnet types, as described in Appendix 3. There was little discussion of other possible magnet types.

The Taskforce confined its deliberations to issues related to commissioning and operating the SSC, avoiding such issues as capital cost, conventional construction, or siting. Similarly, it avoided critiquing details of the existing designs. While these issues are important, they did not fall within the mandate or expertise of the Taskforce.

3. CONCLUSIONS AND SUMMARY

We first present the main conclusions of the Taskforce on Commissioning and Operations, then summarize the findings of the Working groups in somewhat greater detail.

3.1 Conclusions

- **Machines with satisfactory operational characteristics can be built with any of the magnet types now under development.**

  Although there are significant differences among the designs presented to the Taskforce, the Taskforce finds no insurmountable problems with any of the designs from the point of view of achieving the stated SSC goals.

- **There are real differences among the magnet types which result in different operational behavior and flexibility as well as in operating costs.**

- **There are significant questions about operational performance for all of the designs presented.**

  Since none of the designs has been brought to the status required for construction it is difficult to assess the impact on operations which will result from the adoption of a particular design. The issues we refer to include vacuum design in the light of expected synchrotron radiation, reliability, maintainability, required redundancy, insertion systems, beam to beam separation, cryogenic and other machine system interfaces, etc.

- **There is no obvious choice between large and small rings, although there appear to be operational cost differences.**

  In the context of the current designs before the committee, there is an operating cost difference between the large 3T ring and the smaller 6T ring. The larger ring presently has twice as many refrigerators, 80% more tunnel length, a larger RF system (to handle stability problems during injection), a more complex dipole magnet power supply system, and larger abort system. These factors result in a projected yearly SSC operating cost increment which may be 5% to 10% higher for the larger ring option.

With suitable redesign, the operating cost differential might change. Although there is no Taskforce concensus on this point, a discussion of (a) an alternate scenario for laboratory operation and (b) a redesign of the 3T two-in-one machine is given in Appendix B.

The effects of the lower synchrotron radiation power and the potentially better injection field quality of the iron-dominated low-field magnet may outweigh the increased operating cost of the larger ring.

- One-in-one magnets are preferred over two-in-one.

Two-in-one magnets have a potentially lower heat leak due to the smaller surface area, as well as fewer magnet units and other cryogenic parts. The constraints (e.g. possible magnetic coupling, cryogenic coupling, and fixed beam separation) introduced into the design by the closely spaced beams of a two-in-one magnet type lead to the conclusion that a one-in-one design is a more conservative choice. No single item leads to this conclusion, which is instead reached in considering the many ramifications which arise in looking at the whole picture.

A one-in-one design would be preferable from an operational point of view, even at a modest premium in capital cost.

- An over/under bore configuration is preferred to side-by-side.

The advantages of an over/under beam orientation are simpler arrangements for injection and beam abort, less magnetic coupling in a two-in-one type, easier magnet installation and change procedures for one-in-one magnets, and more efficient use of tunnel space. The only advantage of a side-by-side configuration is a somewhat easier lattice for cancelling the dispersion at the interaction regions, which according to the discussion of Section 5 is minor.

- **Low cold mass is preferred.**

  A magnet type with a high cold-iron mass has a simpler support structure and lower magnetic forces on the cold mass; these are important but not operational issues. The disadvantages are a longer cooldown time, a more complicated magnet change procedure, and some difficulty in removing heat generated in the coil from synchrotron light and ramping losses.

Overall conclusions

It is the opinion of the Taskforce that, in regard to operating and commissioning the SSC, the preferential ranking of magnet types is as follows:

1. One-in-one.
2. Two-in-one, magnetically decoupled, over-and-under.
3. Two-in-one, magnetically coupled, side-by-side.

This ordering must be qualified by noting that on some scale the total spread in preference of the Taskforce between the first two choices is perhaps as low as 5% overall. The last design listed lies between 5% and 10% lower on the same scale.

3.2 Summary

The Operations and Commissioning Taskforce was formed to consider the ramifications of various magnets proposed for the SSC. After considerable investigation, the Taskforce concluded that any of the presently proposed magnets would be acceptable from operational and commissioning standpoints. There were no obvious fatal problems in meeting the basic SSC design goals, although each magnet type exhibited strengths and weaknesses. These are discussed in detail elsewhere in this report, and are summarized in this section.

Similarly, there is no overpowering reason to choose the high-field or the low-field option. Nor does the task force consider than any of the currently available designs is necessarily the correct one for the selected field choice.

The taskforce was divided into four subgroups for the purposes of the study:

3.2.1 Cryogenics
3.2.2 Design
3.2.3 Operations
  1. Beam Gymnastics
  2. Operational Cost
3.2.4 Systems

During its deliberations, the Taskforce considered the various types of magnets only in the generic sense, that is, as two-in-one or one-in-one, as high field (5T or 6T), or low field (3T), with or without cold iron, and oriented side by side or over-under. We spent most of our time considering the designs
ubjected to R&D in the past few years, that is, the three Reference Designs,
alled A, B, and C, and the recent Design D. These four designs are described
riefly in Appendix 3. The conclusions apply reasonably well to any magnet
ith similar properties.

It became clear that all of the magnets and machine designs need more work
reach the level of design necessary for final construction of an accelera-
r/storage ring. The Taskforce used its own judgment in deciding which prop-
ties of a particular design were intrinsic to that type of magnet, and which

were merely design choices that could be changed during the further development of that design. An example is the long length of the superferric 3T magnet, which as presented is a single 140 m weldment containing a complete half cell of dipoles, a quadrupole, and a spool piece. It was the feeling of most of the Taskforce that this length in a single weldment was excessive, but that it was not a basic property of the magnet. On the other hand, the low field of the superferric magnet is a basic property, resulting in a larger ring and less synchrotron radiation. The Taskforce tried to ignore those properties that were not basic, but probably did not succeed in all cases.

Following the outline above, we present a brief comparative summary of the various magnet types:

3.2.1 Cryogenics

The following aspects of the magnet cryogenic system were considered:

1. Operating temperature

An operating temperature of 4.5K was taken as an input parameter of all the magnet types, and presented no problem for the existing designs. The superferric type, because of the proposed flow paths, and the lack of mixing of helium near the coil at frequent intervals with cooler helium further from the coils, has a base temperature 0.1K higher than the other designs. Since the magnet will operate conservatively at 4.7K this is not a problem. Because smaller flow channels for cooldown are required in the no-iron design, more helium can be forced into regions near the coils, which are heated by synchrotron radiation and ramping losses. This heat must be removed by conduction through the iron in magnets with large cold mass.

2. Operational heat load

The total operational heat loads below 80K are very similar for all the magnet types. The low-field option has the advantage of less synchrotron radiation load. Two-in-one magnets should have an advantage with regard to heat leaks because of small perimeter, which leads to a smaller radiation head load, and more widely spaced supports as a result of greater rigidity. In particular, the superferric design has a smaller heat leak per meter and less synchrotron power load than any other design. This advantage is offset, however, because the ring is 80% longer than the high field rings. It does retain the advantage of needing fewer heat exchangers (recoolers) in the tunnel, one every 300 m instead of one every 200 m for the high field two-in-one, or two recoolers every 200 m for the high field one-in-one cases. The original high field two-in-one type does not have a lower heat load below 80K than the one-in-one types because its cryostat is quite large and it lacks a 10K shield. It could be modified to incorporate such a shield.

3. Refrigerator design

The designs of the refrigerators and the cryogenics of all the magnets are very similar. They all use single phase liquid helium to cool the coils, removing heat with periodic heat exchangers. Cold gas is returned to the refrigerators from the heat exchangers, the temperature being established by the pressure of the cold gas return.

The basic design difference concerns the length of the ring incorporating the superferric magnet. The requirement for small pressure drops, especially when one of the refrigerators is not functioning properly, sets a maximum length which can be cooled by a single refrigerator. This report considers the present 24-refrigerator version of the 3T design, whereas the 6T designs, with smaller rings, use 12 refrigerators. Since the total heat loads are approximately the same, the refrigerators for the 3T design are each about half the capacity of the refrigerators of the 6T ring. (See Tables 4-7, 4-8, and 4-9.) In developing power needs, we assumed that the efficiency of the smaller refrigerators will be approximately the same as that of the larger, due to the use of higher efficiency equipment available only in the smaller size.

4. Quench behavior

Quench recovery behavior depends mostly on the amount of energy dumped into the coolant. The superferric type has about five times less energy stored in the field per aperture. Since it is expected that both apertures of this two-in-one magnet will quench, a quench will deposit 2.5 times less energy into the helium stream than would be the case for a high field one-in-one magnet, and five times less energy than in a high field two-in-one magnet. If the high field magnets can use a passive protection scheme, this difference will be smaller. A more severe problem, and one that is not well understood, is the pressure rise during a quench. This is expected to be considerably higher in the case of high field magnets, and might require more quench gas relief valves. These valves are subject to failure and are not easily accessible, so it would be attractive to keep the number of them at a minimum.

If that problem is solved, recovery from a full field quench, to the point when the power supplies can be turned on, is expected to take less than 20 minutes in any design (see Appendix 4.7). The final recovery occurs during the ramp.

5. Cooldown from 300K

The cooldown of the complete ring from 300K is expected to be a rare event. However, since large scale cooldowns of the Tevatron have occurred twice in the two years that it has been in operation, the process cannot be ignored. In regard to a full sector cooldown a no-iron design is clearly superior, since it has less thermal mass. It is closely followed by the superferric type, which actually has slightly less thermal mass (enthalpy) per (half sized) refrigerator. These two designs will require up to 100 tons/day of LN_2 in order to cool a sector in about a week (exclusive of steady state usage in the rest of the collider). The heavier designs could require as much as 300 tons/day of LN_2 for a five day cooldown. If the cooldown is stretched to 12 days, the heaviest magnet type (one-in-one, cold iron) would need 125 tons/day of LN_2.

6. Warm-up

The warm-up of magnets must be assisted. It appears that the best way would be to use electric heaters in the cold mass, or to blow warm dry gas through the cryostat. In the case of electric heaters, the warm up can easily be done in a day. The low cold mass magnets will require about 2MW of heater power per sector to do this. This power requirement presents no problem, since it is about the same as the power that would be installed for welders and pumps. The high mass designs (high field,cold iron) would require about twice the installed power.

7. Magnet replacement

The no-iron design has obvious advantages for magnet replacement. Not only does it have low mass, but in the present one-in-one concept only one of the rings must be warmed. This design is the only one in which a section of convenient length can be warmed and cooled in a few days. The advantage is that section valves in the beam pipe, and other equipment will be naturally in place at the warm to cold interfaces during a magnet change. The other designs must accommodate cold gate valves, or one must allow longer times for a magnet change. Even in the best case, a magnet change will take at least a week (Appendix 6.8), compared to three days at the Tevatron; a more conservative time allowance for pumpdown results in an 8 day replacement time (Appendix 4.3).

8. Reliability

It is difficult at this stage to make definite statements about the reliability of the different designs. The best that one can do is count major components and guess at their individual failure rates. The low field types at present require twice as many refrigerators, and at least in that respect are less reliable. On the other hand, the superferric design has fewer recoolers, which are also complicated devices. In order to make a realistic reliability assessment, a detailed engineering study must be made. It should include all major components, not just the cryogenic system.

3.2.2 Design

The impact of magnet style on the design of a collider ring has been considered in light of magnetic field strength, two-in-one or one-in-one magnet types, and side by side vs. over/under configurations. Below, we summarize the effects of present design choices on the criteria of beam stability (single particle or collective), and the relative ease with which certain required beam manipulations can be performed.

1. High field vs. low field

The choice of low field magnets would mean a larger ring circumference, less synchrotron radiation, and improved injection field quality.

The larger ring circumference, given the same relative focussing as in the smaller rings, will lead to a slightly larger beam and larger closed orbit errors. This effect is small, with a 15% difference between the 6T and 3T designs. It is possible that alignment errors will be larger in the low field ring, because of the longer half cell length. Corrections requirements at injection are expected to be significantly less with the iron-dominated low-field option.

The threshold for the onset of single bunch instabilities is dependent upon ring circumference. Stability against the transverse coupled-mode, in particular, requires a larger $\delta p/p$ or injection for the low-field design, with a corresponding increase in the required RF voltage by a factor of at least four. Twenty MV is adequate for full-energy operation of either ring and for injection and ramping of the 6T ring, while at least 80 MV is required while injecting into the 3T ring.

The decreased synchrotron radiation of the low-field design is usually considered an advantage, and it certainly is from a cryogenic and vacuum point of view. From luminosity lifetime considerations, however, it is an advantage to have the additional damping that is present in the 6T ring. In particular, the synchrotron radiation damping counteracts the intrabeam scattering blowup of the emittance and other possible diffusion processes, increasing the luminosity lifetime at 20 TeV from 30 h in the 3T case to as high as 100 h in the 6T case. It should be noted that this only works at or very near 20 TeV. At low energy, the 3T ring has a longer lifetime, since each bunch interacts fewer times.

2. Two-in-one vs. one-in-one

Two-in-one magnets are more likely to have magnetic field coupling, and exhibit whatever consequences follow from the close spacing of the two beam tubes.

It is most important that corrections to closed orbits and tunes in one ring not affect the other ring. It was strongly felt that this independence should be gained by having the correction magnetic fields actually decoupled, as opposed to executing a complicated correction algorithm in one ring when an element is changed in the other. Although there is no evidence that the correction elements are coupled in the two-in-one case, the close spacing of the beams makes the decoupling more difficult. In the worst case, a solution can be found at the expense of a small increase in cryogenic length.

The ability to operate the two rings at different energies for physics was judged not to be an important feature of the SSC. In any case, it is probably forbidden because of the common magnets (quadrupoles and dipoles) in the interaction regions. It might be possible, however, to operate at different energies near the injection energy. This could be useful if the injection lifetime is not high enough, since it takes at least 15 minutes to load each beam. Whether this can be done will depend on the IR design, the seriousness of the long range beam-beam forces, and the overlap-knockout resonances. It is not yet obvious that different energies can be used. Another consequence of coupled fields is that one of the beams cannot be saved if the other is lost. This appears to be of no consequence if one beam is lost after acceleration is started, because beam quality will have deteriorated. In general, higher integrated luminosity will be obtained if the old beam is dumped, and a new one injected.

Another consequence of two-in-one magnets has to do with magnet selection for placement in the ring. This was used to great advantage in the Tevatron, and can be partially credited with the good beam behavior in that machine, since third order driving terms were essentially eliminated by selecting magnets for particular locations from a relatively small sample of magnets. It is clearly true that selection will be considerably more difficult in the case of two-in-one magnets, in that if the probability of finding a proper sequence of magnets from a given supply is P in the one-in-one case, it becomes P^2 in the two-in-one case. The consequences are slower installation, a larger selection buffer, and a larger number of spares.

The close spacing of the rings in the two-in-one case affects the installation of special devices. These include the abort, injection, and RF straight sections, and the special magnets associated with the interaction regions. Conventional magnets will have to be used in the utility regions, especially for the abort system. These magnets are large, and the beams will have to be separated to create space for them. In the IR's there will be very strong quadrupoles. Some of these are common to both beams, but an equal number are separate. In the superferric case it may be necessary to provide added beam separation near the IR's in order to accommodate the insertion quadrupoles. The large spacing of the one-in-one designs does not appear to be a particular disadvantage, since the optics design of the IR's requires long drift spaces in any case.

3.2.3 Operations

1. Beam gymnastics

By beam gymnastics, we mean beam manipulations that must be performed in commissioning and operating the rings. These are subdivided into two groups: those related to single rings, and those that couple the two rings together.

Single ring manipulations. There are a number of small (but not negligible) differences among the magnet types in regard to beam manipulation activities. The comparisons almost invariably favor rings that have the least coupling, whether cryogenic, magnetic, or spatial. In considering commissioning, accelerator studies, and particle physics, we have most carefully looked at injection, beam abort, and acceleration (Appendix 6.1).

During commissioning, it would be advantageous to be able to work on the rings independently, since they will not necessarily be in the same state of readiness at a given time. Such activities as beam commissioning or power supply studies, for example, can be continued on one ring while the other ring is being repaired or is not yet ready. Similarly, accelerator studies would be somewhat more efficient for uncoupled rings. The most efficient use of time would result if the rings are totally uncoupled, the least efficient with rings that are coupled both cryogenically and magnetically. It was concluded in Appendices 6.9 and 6.1 that about 25% of the scheduled accelerator studies time could be accomplished while one of the rings was down for maintainance or repair in the completely decoupled designs. Since 20% of available beam time is typically devoted to studies (Appendix 6.4; see also Appendix 6.1), a 5% increase in particle physics beam time would result with decoupled rings.

For particle physics operation, no significant differences were found, provided that the trim coils can be decoupled in all cases. A detailed study of the magnetic coupling of the trim coil system, as well as the the main magnets, should appropriately be done by the Aperture Taskforce. A brief study was made of other possible particle physics tasks for the machine, such as p-pbar collisions, fixed target physics, gas jets, e-p scattering, etc. (Appendix 6.1). The merits of these extended physics tasks were not considered, and they were all weighted equally. Under those rules, the two-in-one, magnetically coupled style of magnet resulted in an inferior machine. There were no significant differences among the other types.

As with the general considerations discussed above, specific beam operations such as injection and abort tended to favor independent rings. An obvious problem with coupled rings is the close beam spacing, making it difficult to insert the conventional (not superconducting) elements in the two rings. The problems are soluble, but if two-in-one magnets are used the design and construction of the utility areas will be more difficult and probably more expensive. Operation is also likely to be somewhat more difficult.

Ring size also has operational implications. The most obvious is that the installed RF system for a larger ring of low-field magnets will have to be a factor of four larger. In addition, the abort system is more difficult, since the pulsers have to be on twice as long and the dump has to absorb twice the beam energy. It takes an additional half hour to fill both rings in the large ring case, if one uses an injector similar in size to the Reference Designs high energy booster. (As described in Appendix 6.7, the beam-to-beam time is estimated at 2 to 4 hours).

Each one of the considerations mentioned above has small bias in favor of uncoupled rings, and some of them slightly favor smaller rings over larger rings. Although none taken by itself is overwhelming, the net sum of all of them is not insignificant, favoring independent rings.

Ring-to-ring coupling. The major effect studied by the Taskforce was the consequence of magnetic coupling in the two-in-one designs, for the main dipoles and focussing magnets as well as for the trim coils and special magnets. It was assumed that there was no interest in operating the machine at different energies in the two rings for the purpose of physics. On the other hand, it was conceivably useful to be able to operate the rings at different energies near the injection energy, in order to increase the lifetime of one of the beams while the other beam was being injected. It was concluded that if there were no problems with the overlap-knockout resonances, this operation was possible for all magnet types, at least for the body fields of the magnets. Preliminary calculations for the coupling of the end fields indicate that end problems (if any) can be eliminated. Iron around the ends of the 6T magnet is expected to reduce the peak field by a few percent, while for the superferric magnet the addition of sufficient iron to shield the adjacent bore will not reduce the peak field.

It was concluded that the trim coils should be totally independent in the two rings. It appears that this is possible in all designs, although it might require weaker trims in the coupled magnet designs, resulting in a less optimum packing fraction in the bends.

2. Operations and maintenance costs

The cost subgroup of the Taskforce concluded (Appendix 6.11) that minimal yearly operating costs of the laboratory will be about $225M if a 6T ring is built. The number is subject to large uncertainties, and contains no provision for the ongoing innovation which characterizes a healthy laboratory. The figure is about $20M higher for the 3T machine. The operating cost differential between the rings is less uncertain than the total cost. About 3/4 of the cost differential arose from a feature of the assumed model: manned maintenance buildings, coincident with refrigerators, were located at fixed distances around the ring. Since there were 24 such buildings for the 3T ring and 12 for the 6T ring, an additional 150 employees were required, along with more power, supplies, etc. The model may not be correct, but, even if buildings are located more sparsely, there will be some scaling with distance.

3.2.4 Systems

The Systems subgroup considered the impact of the magnet types on quench protection, power supplies, RF, vacuum, correction elements, and beam diagnostics. Although there are major differences in the method used to accomplish these tasks in the various designs, it was concluded that, in sum, the subgroup could make no obvious conclusion to aid in the magnet type selection.

1. Quench protection (Appendix 7.1)

The superferric design seems to allow what superficially appears to be a rather simple passive quench protection scheme. On further study, however, it is not clear that such a scheme has any real advantage. A sophisticated microprocessor is necessary to detect the quench in any case, and to collect data and keep records. Furthermore, calculations indicate that bypass diodes must be installed in the superferric magnets more frequently than at each spool piece, negating one of its major simplifications. Testing the passive system is also more difficult than testing the active system. Since the Tevatron active quench protection system works with high reliability, we can assume that it will also work in the SSC for the high field magnets, which have about the same stored energy per protection unit. The larger 3T magnet can be essentially divided into smaller units for quench protection purposes, presenting no major problems.

2. Power supplies (Appendix 7.2)

The requirement that the betatron tune spread be less than 0.002 implies a current regulation of the order of 2×10^{-5}. This will necessitate a sophisticated regulation scheme for all the possible ring designs. The problem is made more difficult in the superferric design by having three separate high current circuits in the dipoles, and a completely separate quadrupole circuit. Calculations are presently being done to assess the impact of that aspect of the design. Another potential problem is the very slow delay line characteristics of all the designs. This will require considerable feedback to avoid emittance degradation. The problem is somewhat worse in the cosθ magnets, because the delay line is slower by a factor of two.

3. Vacuum (Appendix 7.3)

None of the present vacuum system designs will be adequate to pump down the beam pipe to the level required before cooldown. Pumps of some type will have to be installed between magnets. The length of magnets may be limited by vacuum requirements, and larger beam tubes may even be required. All of this is due to the presence of synchrotron radiation at 20 TeV. In this respect, the low field design, in principle, has a clear advantage, because it has one-fourth the power per meter, and one-half the number of photons per meter as compared with the 6T designs. This should result in a factor of two to four less desorption of gas by synchrotron light. In fact, it is thought that the past history of the beam tube and the condition of its surface may be more important factors. An experiment is currently being conducted at the NSLS to determine the magnitude of desorption effects, and to investigate methods of mitigating the problem. Until the results of that experiment are available, it is difficult to estimate the beam tube vacuum behavior. If the results indicate that the beam tube must be modified in some way, leading to a larger magnet, it will be important to know how the cost and complexity of each magnet type scales with size.

4. Radio frequency system (Appendix 7.5)

In order to satisfy stability requirements at injection, it appears that the RF system of the SSC will be considerably larger in the low field case than in the high field case. The average power consumption will be nearly the same in either case.

4. REPORT OF THE CRYOGENICS GROUP

Introduction

Various aspects of the cryogenic system for the SSC were studied by the Task Force, and are reported in detail in Appendices A4.1 through A4.8. The operational and commissioning characteristics of the possible magnet types dominated the activity. To the extent possible, arguments which will aid in selecting the final magnet type have been developed and are presented in this report.

4.1 Review of cryogenic systems in design report

The most important parameter for the cryogenic system for the SSC is the operating temperature required by the superconductors. Since the current-carrying capacity of the Nb-Ti alloy proposed for the SSC magnets varies as about -12%/K[1]; i.e., current increases as the temperature is lowered, it pays to operate at the lowest convenient temperature.

Gas must be returned through a string of magnets and routed through heat-exchanger columns in each refrigerator before going back to the compressor stations. About 1.2 ata pressure is thus required, corresponding to a temperature of 4.5°K.

The refrigerator capacity must be sufficient to make up both static losses (supports, radiation, etc.) and the dynamic loss during magnet ramping, plus a margin which assures the ability to continue even though the refrigerator may be producing less than maximum capacity (for example, due to accumulation of contamination in heat exchangers), or larger-than-normal heat load from the magnets (poor insulating vacuum due tc small leak). While it is important to have sufficient refrigeration capacity for the SSC, it is necessary not to overdo: near maximum capacity, more than 330 W "at the plug" is consumed for every watt of refrigeration at 4.5 K, and the efficiency is reduced for a refrigerator not operating at near maximum capacity. The helium refrigeration accounts for a major part of the electrical power used by the accelerator-collider complex. In addition, since it is not feasible to turn off the refrigeration during maintenance periods due to the long time constants involved, the refrigerators must be operated many more hours than the machine--probably continuously.

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[1] Corrected for the factor that at a higher current more magnet field is produced in the dipole magnet reducing the current carrying capability of the conductor.

The heat load per refrigerator, as reported in the SSC Reference Design, is given in Table 4-1:

Table 4-1

	Design A			Design B			Design C		
	4K	80K	ℓ/hr	5K	10K	80K	4.5K	10K	80K
Heat load/refrig. (kW)	4.87	20.9	228	2.0	2.4	24	0.60	1.2	11.9

This led the designers to specify the refrigerator capacities shown in Table 4-2:

Table 4-2
Helium refrigerator output

	A	B	C
Helium Refrigeration at 4.5K	7.0 kW	3.0 kW	1.0 kW
Helium Refrigeration at 10K	--	3.6 kW	2.6 kW
Helium Liquefaction	10 g/s	520ℓ/hr	100ℓ/hr
Number of helium refrigerators	12	12	24
Air separation plant's capacity (tons/day of LN_2)	0	86	60
Number of plants	0	4	4

These refrigeration requirements were then used to estimate the AC power demand, as summarized in Table 4-3:

Table 4-3
Cryogenic power.

A	B	C
30 MW at 4.16 kV 6 MW at 480V	26.0 MW (operating) 50.0 MW (installed)	34.25 MW (max. use) 38.2 MW (connected)

At this stage in the development it was generally accepted that all three of the cryogenic systems would, when further perfected and implemented for the SSC, accomplish the objectives of the program and that there were no major distinctions which would allow the selection of the magnet type based on the cryogenics.

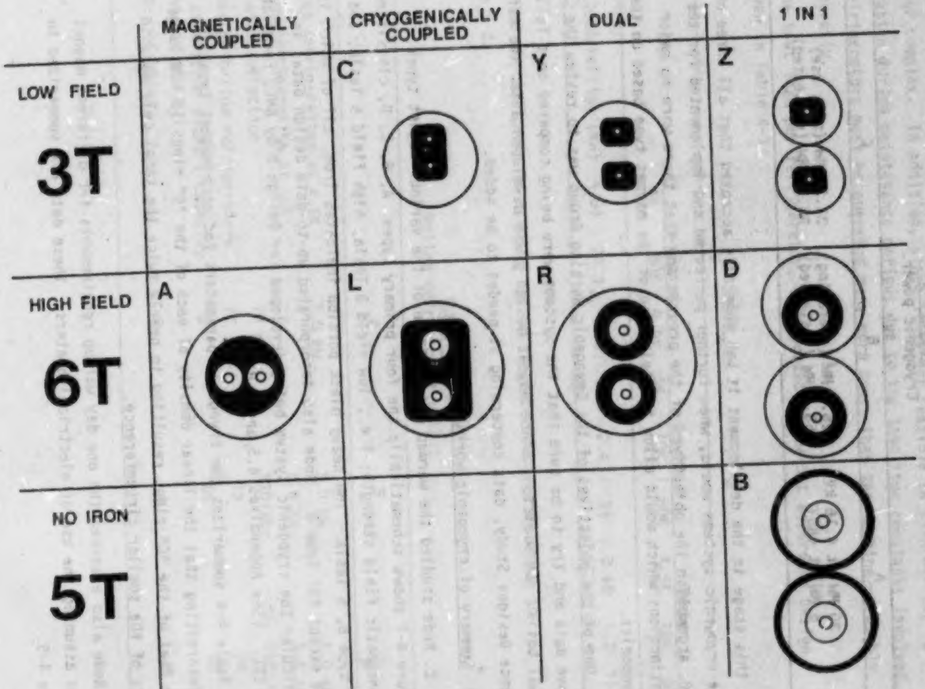
One of the objectives of the Cryogenic Working Group was to review the above data and try to be sure that the systems were being compared on a fully equal basis. In addition, since magnet design D was developed after the Reference Designs Study, data concerning it needed to be added.

4.2 Summary of cryogenic workshop studies

C. Rode studied the warmup and cooldown of the various magnet types. Figure 4-1 shows schematically the four primary types, A, B, C, D, classified by magnetic field strength; i.e., low field 3 Tesla, high field 6 Tesla, and the type B, 5 Tesla. The heavy black portion indicates iron, all of which is cold except for type B. Rode also incorporated up-to-date design data, in particular the cryogenic system being developed for Design D by BNL, Fermilab and LBL. (See Appendixes 4.5 and 4.8)

Table 4-4 summarizes the cryogenic parameters for each magnet type. It is interesting that the linear density of each of the "D" rings is 50% larger than that of the "C" ring, resulting in nearly twice the total cold mass in spite of the smaller circumference.

Rode also examined the one day warmup requirements for different magnet types assuming the use of electrical heaters. These data are summarized in Table 4-5.


MAGNETICALLY COUPLED
CRYOGENICALLY COUPLED
DUAL
1 IN 1
LOW FIELD
3T
HIGH FIELD
6T
NO IRON
5T
C
Y
Z
A
L
R
D
B

2-22-85
C.H.R.

Fig. 4.1. Magnet styles considered by the cryogenics group.

Table 4-4

Cryogenic parameters for different magnet types.

		A 6T	B 5T	C 3T	D 6T
Cold Mass	(MJ)	$5x10^6$	$2.4x10^6$	$3.3x10^6$	$6x10^6$
Cold Mass/Refrigerator	(MJ)	$420x10^3$	$200x10^3$	$140x10^3$	$500x10^3$
Cold Mass/Section	(MJ)	$35x10^3$	$12x10^3$	$3.3x10^3$	$20x10^3$
Number of Refrigerators		12	24	12	12
Sections/Refrigerator		16	42	12	24
Section Length	(m)	1070	150	600	600
Half Cell Length	(m)	107	150	100	100

Table 4-5

Electrical heater requirements for one-day warmup of one sector.

Magnet Type	A	B	C	D
Power Requirement	4.8 MW	2.3 MW	1.6 MW	5.8 MW

Table 4-6 summarizes the liquid nitrogen requirements for the different magnet types, including storage needs. The storage proposed for gaseous and liquid helium is also listed.

The conclusions reached by the study of warmup and cooldown are as follows:

WARMUP -

1. Electric heaters located in the dipoles provide for simple and fast warmup.
2. The electrical power required for installation of magnets in the tunnel (for welders) is a good match to the heater requirements for

Table 4-6

Liquid nitrogen production, storage, and requirements; helium storage.

Magnet Design Type		A	B	C	D
Liquid Nitrogen Production	(tons/day)	0	350	240	500
Liquid Nitrogen Storage Capacity	(tons)	1000	500	2000	2000
Steady-state LN_2 Usage	(tons/day)	0	175	150	?
Full Ring Cooldown	(tons)	12,800	6,100	8,400	15,300
Sector Cooldown	(tons)	1060	510	350	1280
Section Cooldown	(tons)	89	32	8	53
Liquid He Storage	(Kℓ)	1375	480	1500	1500
	(%)	92	33*	167	125
Gaseous He Storage	(Kℓ)	220	220	150	220
% of Total Inventory		15	15	15	20

*Needs to be increased.

the 3T and 5T magnet designs. The 6T magnet may require a considerable increase in the available AC power.

COOLDOWN -

1. Designs B and C have less thermal mass to be cooled, and require up to 100 tons/day of liquid nitrogen in order to cool a sector in about one week (exclusive of steady state usage in the rest of the ring).
2. Designs A and D could require up to ~300 tons/day of LN_2 for a five day cooldown.
3. If the cooldown is increased to 12 days, the heaviest (one-in-one, cold iron) would require 125 tons/day of LN_2.

P. VanderArend studied steady state operations for the different magnet types. His report appears as Appendix 4.2, and summaries of his data are given in Tables 4-7, 4-8, and 4-9. We made the following comments:

4.2.1 General comments

1. Synchrotron radiation contributes the smallest heat load in Design C. Heat is removed differently in different magnet types. The heat flux from the synchrotron radiation appears on the inside of the magnet coil, and liquid helium flowing in the inner channel is unable to remove this heat without a temperature increase. For magnets A, B, and D the magnet lengths are short enough that the slightly warm liquid mixes with the bulk flow in between magnets and an acceptable magnet coil temperature is maintained. In long magnets (like the C design) the heat from the synchrotron radiation must be conducted away through the coils. Since in this case the load is low the transfer can be accomplished by lowering the coolant temperature by ~0.1°K.
2. Table 4-7 shows a significant difference in heat leak to the 4.5°K temperature level between A magnets and the B, C, and D magnets. The low values of B, C, and D magnets are the result of use of an intermediate temperature shield. In order to compare the 4.5°K heat-leak values, intermediate shield heat leak for B, C, and D magnets must be added to the 4.5°K temperature heat leak, so that the heat leaks for

all four magnets are about the same. It should be noted that these values are much lower than those attained in the Tevatron. Since heat-leak values of approximately 0.009 W/ft^2 are routinely achieved in commercial practice, it appears that the heat leaks used are realistic.

3. The total heat leak below 80°K for the four magnet types is the same, when intermediate shield temperature is appropriately taken into account. Since the Design C magnet ring is twice the length of the type B ring, it is only equivalent by virtue of the fact type C magnets are lighter and have a smaller exposed area for heat leak. As the designs are perfected, this comparison will need to be updated.
4. Refrigerators for the A, B, and D magnets are roughly the same size, while the refrigerators for the type C system are half as large. It appears that in this size range the C system refrigerators can be expected to have approximately the same efficiency as those for the A, B, and D systems.
5. Design refrigerator capacity includes approximately 50% extra capacity over steady state requirements. The extra capacity has two functions:
    a. it allows for any inaccuracy in estimating heat loads,
    b. it provides extra capacity in case of refrigerator failure.

It is essential that as magnet designs evolve the heat loads be updated and refrigerator capacity changed to match the new conditions. The provision for two adjacent refrigerators picking up the load of a failed refrigerator is only useful when extra refrigeration can be transported over the longer distance. This consideration makes the use of an intermediate shield very attractive, because of the decreased heat load on the 4.5°K system. At the same time, the absolute temperature of the intermediate shield is not critical and can be allowed to fluctuate by a few degrees.

The liquefier capacity of the refrigerators has to be matched to total flow required by the high-current vapor-cooled leads.

6. The type C magnet system described in the RDS has twice the number of refrigerators. This results in the length of magnets cooled by a given refrigerator being approximately the same. It is important that the distance between adjacent refrigerators be such that a single refrigerator failure does not result in the interruption of operations.

7. Liquid helium storage capability is a function of the magnet system inventory. All four magnet systems are capable of storing all of the helium in liquid form when the system is not operational. This also facilitates magnet system cooldown and fill, where the stored refrigeration reduces the required time.

8. Even though the cooling requirement for the electrical leads will be defined exactly only when the final leads are selected, it is generally accepted that a flow of 0.06 g/s per 1000A lead is reasonable. Therefore, it is possible to define liquefaction requirements at least roughly by using the total current flowing through the leads.

9. Single-phase flow rate for the type B magnet system is 100 g/s per channel. This flow rate with the specified spacing of heat exchangers results in a temperature rise of only 0.06°K. This allows for surprises in heat leak and for single refrigerator failure. The type A magnet system requires an increased flow rate when a refrigerator fails.

   The type A, B, and D magnets employ 1ø liquid at 4 atm. At this pressure the specific heat is 78% of that at 2 atm. This means that with all other things being equal, type C magnets 1ø flow has approximately 25% more heat absorption capability.

10. The coil temperature is 4.5°K for all magnet types. This temperature is taken as an input parameter. It is questionable whether the lowest pressure in the refrigerator can be above atmospheric without the use of a cold-gas pump.

11. The single-phase flow rate through the magnets is proportional to distance and heat leak per unit length for a given temperature increase. Low heat leak allows greater spacing of heat exchangers and/or lower flow rates. Both are important, because flow rate generates pressure drop which in turn affects the temperature at which liquid helium boils. Typically, a pressure drop of 3 psi in the 4.5°K vapor return line means a 0.2°K temperature rise of the magnets when traversing the magnets from refrigerator to turnaround point.

    The pressure drop becomes more significant when considering the case of one failing refrigerator with two adjacent refrigerators carrying the load.

4.2.2 Comments concerning the 4.5°K system (Table 4-7)

The most significant difference between A magnets and B, C, and D magnets is the intermediate shield. When such a shield is used:

1. Heat leak between the 4.5° parts and the 80°K shield is not nearly as critical.
2. Heat exchangers for removal of 1φ fluid heat are much smaller.
3. For the same size pipes, pressure drops in the 1φ liquid flow and 4.5°K vapor flow are much smaller.

   Because of this, it will be much easier for adjacent refrigerators to assume the load of a nonoperating refrigerator.
4. The extra pipe for intermediate shield flow provides a convenient circuit for cooldown and warmup.
5. Power required by the refrigeration system will be lower when the intermediate shield is used. (See Appendix 4.5.)

   On the other hand, it is more expensive to include an extra shield in the cryostat, and the extra pipe and shield may make the cryostat vacuum shell somewhat larger.

4.2.3 10-20°K temperature level (Table 4-8)

1. The heat leak per unit surface area is assumed larger than achieved in good commercial practice, to provide a safety factor.
2. In the present type A, B, and C designs, shield flow rate is generated from 4.5°K vapor. This in turn is a product of the heat exchangers cooling single-phase flow. As a result flow rate is variable and increases when approaching the refrigerator.
3. In one of the options being studied for the type D cryostat (Case "C" in Appendix 4.5), intermediate heat shield cooling gas is obtained from the heat exchanger at 15°. This permits a more than threefold efficiency increase, and consequent operating cost reduction. This can in principle be done with any design, although the particular plumbing used (out along one ring, return along the other) is simplest in a one-in-one design. (However, see Appendix 8.)
4. The temperature at the exit of the shield (entry to the refrigerator) may vary considerably. For instance, as a result of a quench, part of the shield line may be filled with warmer vapor generated by the quench.
5. The pressure drop in the shield line needs to be small, in order to keep the heat exchanger shell side boiling at a low pressure. The alternative to a low pressure drop is the use of a cold gas pump which pumps shield gas from a pressure of 0.9-1.0 atm to 1.2 atm.

4.2.4 80°K shield (Table 4-9)

1. The heat leak to the shield is assumed to be comparable to that achieved in commercial practice. The absolute value is not critical, as long as liquid nitrogen in sufficient quantity can be transported through the shield supply lines.
2. Liquid nitrogen takes up heat and remains subcooled throughout the circuit. Heat is removed at the refrigerator stations through heat exchangers with boiling liquid nitrogen.

3. For all magnet designs, liquid nitrogen is subcooled below 78°K and therefore requires vacuum pumps. The subcooling is especially useful when rapid depressurization to atmospheric pressure occurs. As long as the liquid is below 78°K, large increases in volume due to boiling are avoided.

Table 4-7

Steady state operation
4.5°K parameters
(Abstracted from Table A4.2-1)

Magnet Type		A	B	C	D
1. Synchrotron Radiation	W/m	.216	.129	.0579	.194
2. Heat Leak	W/m	.49	2x.0590	.0476	2x.056
3. Total for 2 Rings	kW	54.0	24.0	16.4	26.4
4. Heat Load per Refrigerator	W	4500	2000	683	2200
5. Refrigerator Capacity	W	7000	3000	1000	3300
6. Refr. Liq. Helium Cap.	ℓ/hr	288	520	130	680
7. Number of Refrigerators		12	12	24	12
8. Liquid Helium Storage Capacity (gallons)x 10^{-3}		12x33	12x30	24x18	12x30
9. Liquid He Volume x10^{-6}	ℓ	1.5	1.5	0.9	1.2
10. Lead Flow total	ℓ/hr	2532	3120	2100	4080
11. Total Amp. of Leads x10^{-6} (main power leads)		1.06	1.15	1.08	1.15
12. 1ø He flowrate	g/s	140	2x100	56.5	2x100
13. Number of Exchangers		432	960	504	864
14. Distance Between 1ø Heat Exchangers	m	200	214	300	200
15. He Temperature at the Coil	°K	4.5	4.5	4.5	4.55
16. Thermal Mass per Refrigerator	Jx10^{-9}	324	200	132	445
17. Cold Mass	(kg/m)	605	2x79.5	250	2x373

Footnotes to Table 4-7

Line 1

Values are based on a half cell length: in the case of the one in one type magnets, numbers are given per unit and total is two times.

Line 2

Numbers for B and D magnets are based on the total calculated load per refrigerator, divided by the length in meters per refrigerator.

Line 3

Indicates total refrigeration load at 4.5°K. Liquefaction requirements for leads are listed under lines 11 and 12.

Line 4

Indicates number of line 3 divided by number of parallel refrigerators.

Line 9

Indicates total inventory of helium in the 2 rings, expressed in equivalent liters of liquid helium. The accuracy of these numbers is probably considerably less than that of numbers in the table. It is likely that the numbers are somewhat low since a number of components have not been designed.

Line 10

Correction element leads can represent a fairly large fraction of the total. The exact number for the correction leads of the C magnet is quite uncertain at this time. For the D type magnet, only 40% of the flow is set aside for the main leads. Main power leads consume 1.44 ℓ/h of liquid per kA for the A, B, and D magnets and 1.73 ℓ/h of liquid per kA for the C magnets.

While these numbers are based on the type C magnet system described in the RDS, more recent revisions have increased the number of dipole circuits and consequently the lead losses. Currents are described in Appendix 7.2, and the revised lead losses in Table A6.11-4.

Table 4-8

Steady state operation
Intermediate shield parameters
(Abstracted from Table A4.2-2)

Magnet Type		A	B	C	D
19. Heat Leak	W/m	–	2x.121	.217	2x.181
20. Total for Ring	kW		28.80	33.86	31.2
21. Shield Flowrate	g/s	–	2.0-52.0	36.3	100
22. Temperature in	°K	–	4.35	4.4	~15
23. Temperature out	°K	–	8.0	10.7	~18
24. Pressure Drop	ata	–	.01	.1	.5
25. Pressure in	ata	–	1.123	1.1	3.5
26. Cold Mass	(kg/m)	–	2x10.3	9.1	2x12.1
27. Thermal Mass per Refrigerator	$J \times 10^{-9}$	–	24.7	4.8	29.0
28. Surface Area	ft^2/m	–	2x9.6	10.6	2x14.6

Table 4-9

Steady state operation
80°K shield parameters
(Abstracted from Table A4.2-3)

Magnet Type		A	B	C	D
29. Heat Leak	W/m	2.40	2x1.41	1.614	2x1.67
30. Total for Ring	kW	251	238	292	288
31. Flowrate	g/s	400	325-475	293.5	300-600
32. Temperature in	°K	70	74	75	74
33. Temperature out	°K	90	89	85	89
34. Pressure in	ata	5	5	6.0	5
35. Pressure drop	ata	1	1	1.5	1
36. Number of Liquid N_2 Pumps		12	12	24	12
37. Number of Heat Exchangers		12	24	24	24
38. Cold Mass	Kg/m	18.2	2x10.7	10.2	2x14.3
39. Thermal Mass per Refrigerator	$J\times10^{-9}$	19.8	31.2	5.2	35.2
40. Surface Area	ft^2/m	20.6	2x12.4	12.2	2x12.0
41. Number of N_2 Plants		0	4	4	2
42. N_2 Plant Capacity	tons/day	0	86	60	170

5. REPORT OF THE DESIGN GROUP

Introduction

In this section we discuss the key advantages and disadvantages of the different magnet styles presently under discussion, from the viewpoint of accelerator physics. In doing so, we will de-emphasize aspects of particular magnet designs that appear to be incidental and easily modified, and focus on the essential features and differences. Outstanding among these are the magnetic field strength B, the degree of magnetic coupling (crosstalk), and finally geometric properties such as bore-to-bore distance and relative orientation. More specifically, we will outline the implications of high (~6T) field vs low (~3T) field, the relative advantages of side by side vs. over/under arrangements, and explore the issues of two-in-one vs. one-in-one designs.

We will also touch briefly upon the questions of field quality. Although of prime importance in the overall assessment of machine performance, it is of limited relevance for the discussion of the issues at hand, in that it seems to provide only limited selective leverage with regard to magnet style.

Criteria for rating magnet designs are provided by considerations of beam stability, single particle and/or collective phenomena, and beam performance as affected by magnet type-driven machine design aspects. Another set of criteria follows from considering the relative ease with which certain feats of "beam gymnastics" can be performed, either in the process of commissioning or in day-to-day operation.

5.1 Comparison of high and low magnetic field levels

In the following, we identify aspects of beam behavior and/or machine design that depend primarily on the magnetic field level, either directly or as a consequence of the different ring size.

5.1.1 Scaling of lattice functions

If a given fraction of the machine circumference C is occupied by quadrupole magnets, and if there is a fixed ratio between dipole field B and quadrupole gradient G, then the tune Q scales as $C^{1/2}$. As an immediate corollary we obtain the same scaling law for cell length L, the number of cells N_c, and the beta function β in the regular arcs. The maximum dispersion is proportional to C/Q^2 and remains approximately constant. Beam size, for a given emittance, therefore scales as $C^{1/4}$. Assuming that displacements, tilts and dipole field errors are independent of C, closed orbit errors also scale as $C^{1/4}$. Since the ring sizes under consideration differ only by a factor of two, the difference is only ~15% and is hardly significant. However, it is conjectured that errors of alignment might actually increase with increasing C.

5.1.2 Collective effects

The only size dependent factor in the simple equation relating longitudinal impedance Z /n with the threshold current for onset of longitudinal microwave instabilties is the square of the transition γ, which scales as C^{-1}. Therefore

$$(Z_\ell/n)_{\text{threshold}} = C^{-1} .$$

The Reference Designs Study has shown that if all other relevant parameters are kept the same, the longitudinal microwave instability is a less severe constraint in the SSC than the transverse mode coupling, or the fast head-tail instability. To be stable at a given current and for given values of the impedance and the lattice functions, the beam must have a minimum rms energy spread $\sigma_\gamma = \sigma_E/m_p$. As discussed in Appendix 5.1, this energy spread must be larger for the 3T ring. The required increase is not sufficiently large to rule out 3T magnets of small bore but makes collective effects a particularly important issue. In the more pessimistic configurations $\sigma_{\gamma\text{min}}$ may be large enough to approach or exceed the momentum aperture available with the proposed magnet.

5.1.3 RF voltage voltage requirements for 3T and 6T rings

As discussed in the RDS, the RF voltage required to suppress longitudinal emittance growth during collider operation is

$$V_{RF} = \frac{3\pi\, m_p}{eF}\;\frac{1}{\gamma}\;\frac{f_{RF}}{f_0\gamma_t^{\,2}}\;\sigma_\gamma^{\,2}$$

where

F = bucket-filling factor. The maximum acceptable value is set by RF noise, which at present is largely unknown.

f_0 = beam frequency, inversely proportional to the machine circumference C.

γ_t = transition gamma, proportional to the tune Q. As mentioned in Section 5.1.1, Q scales nearly as the square root of C.

σ_γ = beam r.m.s. energy spread in units of the proton mass.

and other variables have their usual meanings.

There are three regions of interest:

1. Injection. Here the transverse mode-coupling instability dominates; it can be stabilized by requiring

$$\sigma_\gamma = \frac{I_B Z_T e}{4\sqrt{\pi}\, m_p} \frac{\bar{\beta}}{\eta} \cdot$$

where

I_B = current per bunch. Since the total current is the same for 3T and 6T rings, the current per bunch scales as 1/C.

Z_T = transverse impedance of the machine. It is dominated by the contributions of beam pickups and bellows, which scale as the tune and as the (beam tube size)$^{-3}$. The beam tube size is the dominant factor.

$\bar{\beta}$ = average amplitude factor, proportional to C/Q.

η = $(1/\gamma_t^2 - 1/\gamma^2) \approx 1/\gamma_t^2$, so η is proportional to $1/Q^2$.

With these scalings, σ_γ is seen to go as $Z_T Q$. Since V_{RF} is proportional to $(C/Q^2)\sigma_\gamma^2$, it goes as CZ_T^2 under injection conditions. For the 6T machine $\sigma_\gamma = 0.15$ is sufficient, so, using the rest of the RDS parameters, one obtains 8.7 MV for the required RF voltage at injection. We conservatively round it to 10 MV.

The main uncertainty in scaling this figure to the 3T machine comes from Z_T, which enters quadratically. In Appendix 7.5 it is estimated to be twice a large as in the 6T case, while estimates in Appendix 5.1 range to even larger ratios. Taking a factor of two as a conservative lower limit, we find that at least eight times as much RF voltage is required at injection, or at least 80 MV.

2. Acceleration. As can be seen from Fig. 4.6-2 of the RDS, the highest RF voltage is required at the beginning, where stability against transverse mode-coupling problems must be maintained while ramping at an assumed constant rate. The voltage requirement is substantially decreased if the latter requirement is relaxed, which can be done even without a large penalty in total acceleration time. Since the voltage can be substantially below that required for injection (in the 3T machine) or operation at full energy (in either machine), it presents no new requirement.

3. Colliding beam conditions. At full energy the main problem is obtaining a long lifetime in the presence of intra-beam scattering, which can be done by increasing σ_γ to about 1.0 for either machine. In this case, (a) V_{RF} is nearly independent of machine size by the scaling arguments presented above, and (b) 20 MV is sufficient.

In conclusion: The 6T machine must provide 20 MV for stability during colliding beam operation, and this is sufficient for both injection and acceleration. The 3T machine also requires 20 MV for full-energy operation, but must provide 80 MV during injection. Implications for power consumption and operation cost are discussed elsewhere in this report.

5.1.4 Synchrotron radiation and luminosity lifetime

In comparing high field vs. low field rings, the two most interesting parameters describing synchrotron radiation are the transverse damping time and the total synchrotron radiated power, which must be absorbed at 4K.

For protons with $\gamma = 2.13\times10^4$ (i.e. 20 TeV) the total power radiated in watts is

$$P = 8.69\times10^{-7}\,(B/1T)\,\lambda \quad . \tag{1}$$

where the average linear density $\lambda = 1.45\times10^9$/m under the RDS parameter assumptions. If machines of different radius have the same emittance, bunch spacing, etc., then Eq. (1) shows that the radiated power per unit length scales just as B.

Transverse damping times, again at $\gamma = 2.13 \times 10^4$, are given by

$$\tau_x^{-1} = \frac{1}{\epsilon_x}\left(\frac{d\epsilon_x}{dt}\right)^{-1} = 3.66\,\frac{(C/1m)}{(B/1T)} \tag{2}$$

For B = 6T and C = 100 km the damping time is therefore ≈ 17 hours, while the corresponding value for B = 3T and C = 170 km is ≈ 58 hours.

To compare luminosity lifetimes, observe that the following holds:

$$\tau_L^{-1} = \frac{1}{L}\frac{dL}{dt} \approx \frac{2}{N}\frac{dN}{dt} - \frac{1}{\epsilon}\frac{d\epsilon}{dt} \tag{3}$$

Particle losses mostly occur in the interaction regions. Assuming 6 IR's, a total cross section of 200 mb, and a luminosity of 10^{33} $cm^{-2}s^{-1}$ in each IR, it follows that $dN/dt = 1.2 \times 10^9 s^{-1}$. ($N \approx 1.4 \times 10^{14}$ in the 6T ring, and 2.4×10^{14} in the 3T ring.) With reasonably good vacuum, beam parameters adjusted for sufficiently slow intra-beam scattering growth, and neglecting blowup due to nonlinear effects due to either magnet imperfections or the beam-beam interaction, we observe that the rate of change of the emittance is controlled by synchrotron radiation damping in the high field case while at 3T the damping is just about fast enough to compensate for growth due to various scattering processes. Making some allowance for the latter, we obtain 30 hours $< \tau_L <$ 100 hours for the luminosity lifetime in the high field case, and τ_L = 30 hours for the low field case. The upper value (high field case) applies if the emittance damps at the natural rate, the lower one if measures are taken to maintain the beam-beam interaction at constant strength. Synchrotron radiation thus enhances lifetime for full energy operation in the higher field case, and provides an added measure of insurance against various diffusion mechanisms in all phase planes. This advantage is realized only at or close to peak energy however, and for example at E = 10 TeV, the low field ring would exhibit the longer lifetime at the same luminosity.

5.1.5 Summary

The only significant advantage of low field magnets appears to be that they force a large circumference that eventually may be filled with high field magnets. On the other hand, no crippling disadvantages have been discovered so far. Impedance analysis and the study of collective effects acquire particular importance in this context, and seem to lead to momentum spread requirements that demand significantly larger RF systems than are described in the RDS.

5.2 The issues of coupling vs. independence

The extent to which one beam is affected by manipulations of the other or by the configuration of the other ring is an important operational issue. Different degrees of independence and a rating of their operational importance will be given in the "Operations Group" report, and we will only briefly highlight the most important aspects.

5.2.1 Elements of independence and rationale for minimum coupling

We may identify the following categories of independence:

a) Capability to operate one ring for beam dynamics studies e.g., while the other is down due to a magnet malfunction. The desirability of this feature depends on the expected frequency of such occurrences. To meet this requirement it is obviously necessary that the main ring magnets be cryogenically independent so that operation of one ring is possible during warmup and cooldown of the other.

b) Transparency of beam manipulations: It is of the utmost importance that routine operations such as closed orbit changes/corrections, tune and chromaticity adjustments will affect the other beam at most minimally and predictably. In the interest of straight-forward implementation and simplicity, it is unanimously agreed that this property must be achieved by the magnetic and mechanical design of correction magnets, rather than by sophisticated software that would attempt to counteract the effects of coupling. To give an extreme example of "software only" decoupling, it might be necessary to demand changes in all correction elements when only a single parameter is to be changed.

c) *The capability to operate at different energies:* The desirability of this flexibility has often been expressed, although hard and convincing arguments for its necessity have not been advanced so far. Operation for HEP running with the beams at different energies is generally not considered important. Reloading only one beam after it has been aborted, without significantly affecting the other, is not considered advantageous from the point of view of gains in the average luminosity (Appendix 6.7). There remains an important possibility: Injection lifetime may be marginal at 1 TeV but quite good at a higher energy, say 3 TeV. A prudent designer might well allow the possibility of slightly accelerating one beam before injecting the other. However, the underlying reasoning may well prove fallacious: It might well be argued that one should simply design for adequate lifetime. From an engineering point of view it would seem that if the indicated maneuver has any merit, the situation would already be marginal and desperate.

So far we have not mentioned the interaction between the two beams through long range beam-beam forces. Of particular concern are the so-called overlap-knock-out resonances observed to occur when bunched beams of unequal energy interact. Preliminary investigations (Appendices 5.2 and 5.3) show the problem to be quite real The effects are nonnegligible, and the resonances are closely spaced, so that the tune spread will very likely straddle one or more of them. Furthermore, during acceleration these resonances will be crossed as both beams are brought to equal energies. The could be avoided if the revolution frequencies were kept the same by changing the beam orbits, an approach demanding almost 10 mm of precious additional space in the magnet aperture. Feedback systems must certainly be invoked. A complete and definitive assessment must await further investigation. The feasibility of running unequal energy beams, independent of magnet or ring design, is not proved beyond doubt.

5.2.2 Design and magnet selection consequences

The postulated degree of independence of the two rings from each other requires (i) an interaction region design allowing beams of different energies, (ii) main ring magnets allowing ratios of a few between beam energies, at least when one beam is at 1 TeV, and (iii) correction elements which are essentially crosstalk-free.

A schematic IR layout is shown in Fig. 5-1, in which are identified the common quadrupoles that strongly couple the beams and the (partially common) separation dipoles. Two aspects must be solved: beam steering and focussing. Recent design work has come very close to proving the existence of smooth transitions from fully powered to completely turned off IR quadrupoles that leave the machine tune invariant. Being able to turn off completely the IR quads is an essential feature for an unequal energy IR. One must then find a solution for the dipoles. Work on this problem is in progress, and has produced at least one example solution.

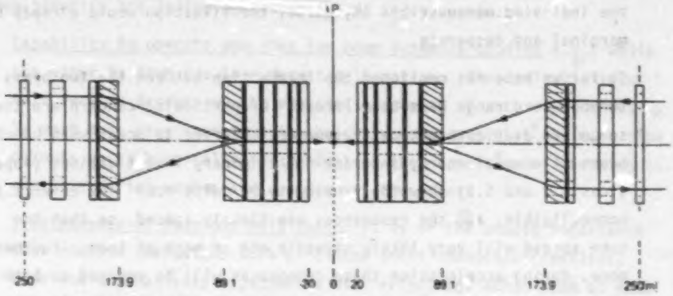


Fig. 5-1. IR layout. Dipoles are shaded. Quadrupoles between the dipoles closest to the interaction point are common to both beams, and of necessity strongly couple the beams.

The degree of magnetic dependence in the various designs will be discussed more thoroughly by the operations group. We summarize by stating that all proposed magnets can be made to satisfy the stated requirements.

5.3 Lattice design implications

After careful consideration, the general conclusion reached by the group was that there are simply no essential optics and lattice design consequences following from the choice of magnet style. The design of injection and abort system layouts, as well as that of the lattice in the utility straight sections, will look slightly different but no consequences of significant technical or economical impact have arisen.

Injection layouts appear to be equally difficult or easy whether over/under or side by side magnets are chosen. One favors injection in the horizontal plane, the other in the vertical plane.

It was long thought that the simplest way of controlling the dispersion at the IR produced by the beam separation dipoles, i.e. the introduction of an achromatic vertical bend, would result in an increase in length of 1 to 2 km per IR for the over/under configuration. In the side-by-side configuration the normal (horizontal) dispersion killers could be used (by being made carefully "imperfect") to compensate for the effects of the beam separation dipoles. This may no longer be true if tuning trombones are actually used because they require that there be no dispersion within their length. This might lead to a lengthier arrangement in the horizontal case as well.

5.4 The role of field quality

Magnetic field quality is one of the most crucial beam dynamics issues of the SSC. Largely determined by aperture size, coil design and fabrication tolerances, field quality in turn determines the maximum stable betatron amplitudes and energy deviations. These issues have been considered in detail by the Aperture Task Force. Despite their important role, the field quality issues provide little selective leverage in the present context.

All statements that might be made about cosθ (high field) magnets apply with one exception to all styles. The exception is in the appearance of multipole terms due to iron saturation near full field, which is most pronounced in the coupled, close-in iron two-in-one magnets, i.e. the now-defunct version of design A described in the RDS.

The significant difference between high and low field magnets is in the different roles that persistent currents and iron saturation play. Both are controllable, at present locally. In the case of the superferric magnets three independent current loops are proposed. At least three different methods are described for cosθ magnets, of which two are passive in nature.

If magnet selection ("shuffling") is considered, two-in-one magnets carry a heavy penalty: If the probability of finding a satisfactory sequence of magnets from a given supply is P for a single bore, it is decreased to P^2 for two-in-one magnets. This issue has not been sufficiently addressed and deserves further attention.

6. REPORT OF THE OPERATIONS GROUP

Introduction

The Operations Group broke up into two subsections, the Beam Gymnastics group and the Operation and Maintenance group. The Beam Gymnastics group generally looked at issues involved in the commissioning and operation of the collider from the beam dynamics point of view and the operating, and maintenance group considered the issues of operating cost, configuration, complexity, repair and replacement.

The detailed report of the Beam Gymnastics group appears as Appendix 6.1, which is supported by Appendices 6.2-6.7. Appendices 6.8-6.11 document the conclusions of the Maintenance group. Because of its relevance, a CERN report on SPS operation is included as Appendix 6.12.

6.1 Beam gymnastics

In discussing the influence of magnet style on the ease of SSC beam gymnastics, it is convenient to divide specific accelerator-related issues into two groups: those related to single-ring manipulations such as injection and abort, and those which couple the two rings together. It is also of interest to discuss more general topics such as reliability, and to take a brief look at possibilities for other accelerator uses.

6.1.2 Beam gymnastics in uncoupled rings.

We discuss first the effect of magnet style on rather general SSC activities: commissioning, accelerator studies, and particle physics. There are small (but not negligible) differences which favor rings with the least coupling, either cryogenic, magnetic, or spatial. In commissioning, for example, the work on the two rings will generally not be at the same stage, and it is advantageous to be able to work on them independently. However, because of the strong and probably unavoidable coupling through the IR magnets, the net advantage of one-in-one Designs B and D with respect to the two-in-one Designs A and C is not likely to be a large one.

Much the same argument applies to accelerator studies, since if the rings are in separate cryostats studies can proceed in one ring while, for example, a magnet is being replaced in the other ring. From ISR experience (Appendix 6.4), accelerator studies are expected to be crucial to long-term gains in luminosity. Detailed models were developed for the distribution of time and causes of downtime to study the net advantage to uncoupled rings (Appendices 6.1 and 6.9). This was estimated to be equivalent to 5% of the hours available for particle physics.

For particle physics operation (20 TeV p-p collider) itself no differences were found. This conclusion is subject to the caveat that satisfactory solutions are found to decoupling the trim coils, as is thought to be possible.

The discussion of general SSC tasks, such as commissioning and accelerator studies, was extended to include a brief survey of possible new physics tasks. The new tasks considered were proton-antiproton collisions in one or two rings, polarized proton collisions with a gas jet target or with high energy polarized protons, electron-proton collisions, fixed target physics, proton-proton collisions at asymmetric energy, and heavy ion collisions. The usefulness of the magnet types for each of these tasks was estimated and collected in a table (Table A6.1.3.1), with no weighting as to the relative importance of the physics. Not surprisingly, the magnets with the least degree of coupling do the best. If each physics task is weighted equally and the scores are summed, the differences between Designs B, C, and D are found to be small, but Design A does significantly worse.

We now discuss the effect of magnet style on specific beam gymnastics activities, such as injection and abort. A major concern at injection is beam loss which causes quenches. To minimize these effects, the RDS assumed the use of conventional magnets in the injection straight sections. These magnets are more difficult to design for magnet styles which have small beam separation, such as Designs A and C. Beam loss due to misfiring injection kickers can quench magnets several betatron wave lengths away from the injection area itself, but, based on Tevatron experience, this will not be an important problem for the SSC. The fill time for a 3T SSC is 30 minutes longer than it is for a 6T machine, assuming a 6T high energy booster. The advantage to higher field magnets is small, since the overall fill time is estimated at 2 to 4 hours and the fill will be kept for about 8 hours (Appendix 6.7). The effects of superconductor magnetization, which are largest at injection, will complicate the operation of $\cos\theta$ magnets somewhat.

Beam acceleration will require twice the RF power for the longer 3T rings than for the 6T rings. The only operational penalty will be increased downtime due to RF problems (1%-2%).

Rings with large beam separation will require more bending for interaction region injection, but this may not result in increased cryogenic length. It is clear, however, that the design of the high-gradient quadrupoles will be much more difficult (or perhaps impossible) for small beam separations. The Design Group (Section 5) has reviewed the effect of ring orientation on IR design and found no significant differences.

The abort system is a critical area because of the potential for quenching or damaging magnets. However, the differences between the magnet styles are not large. For example, the maximum time between sensing a quench and firing the abort system is 0.8ms for 6T magnets and twice as long for 3T magnets, but this time is small compared to the typical time during which a quench develops (tens of milliseconds), so the overall difference is minor. Similarly, the abort system must remain on twice as long for the low-field magnets, but this presents no serious design problem. The factor-of-two difference in total stored energy in the beams (400 MJ vs 800 MJ) places added demands on the beam dump, but these can be met with added defocusing of the beam or by moving the dump further away. Rings with small beam separations require additional beam manipulations by the abort system, in order to make space for the necessary conventional magnets which make up its beam transport system, but nothing fundamentally different is required. Again, additional manipulations are required for the abort system for side-by-side magnets, as opposed to an over-under configuration, but the effects are small.

6.1.3 Ring-to-ring coupling

Although specific field quality requirements for the SSC have not been set, it is assumed on the basis of the Tevatron and CBA designs that dipole uniformity at the level of a few parts in 10^4 is desired. Since the effect of ring-to-ring coupling will be but one of several contributors to the total, a level of one part is 10^4 is taken as working value for an upper limit to the effects of coupling. (It is also desirable that coupling not move the closed orbit by move than ±1 mm, based on ISR experience. However, no analysis of the effect on closed orbits has been done for this report.) In calculating the effects of coupling, all possible combinations of currents must be examined. This is of particular importance for the trim coils. For the main dipoles, we restrict our examination to asymmetric excitation up to a few times the field at injection. (Magnets which are uncoupled when run at different fields near injection energies are seen as possibly providing a safety margin for the 1 TeV beam lifetime, although problems with overlap knockout resonances may be insurmountable.*) Operation at different but high energies greatly complicates IR design and is not treated in the report, except to note that asymmetric energy operation above 5 TeV is not possible with the magnetically coupled two-in-one dipole. If asymmetric operation at high energy were important, the rapid change of μ with B would be a problem for Design C of fields near 1.5T (Appendix 6.3).

We begin by examining coupling between central sections of the main dipoles, near injection fields. The variable space between rings of Design B or D magnets allows the coupling to be reduced to arbitrarily small values, as is confirmed by calculation. Calculations for both of the two-in-one magnets, designs A and C, indicate that these rings are also satisfactory for asymmetric operation between 1 TeV and 5 TeV. Preliminary calculations of the stray fields due to the ends of the one-in-one cosθ designs (e.g., Appendix 6.5) and the superferric designs indicate that coupling to the adjacent ring is satisfactorily small. If it is not possible to find a satisfactory solution for coupling due to unshielded ends of Design A, the iron yoke can be extended to cover the ends, at the expense of a few percent in peak field. Because the quadrupoles have lower fields and less leakage and coupling than the dipoles, it was assumed that their coupling was satisfactorily small in all designs.

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*S. Meyers (SSC-14), and A. Chao and C. W. Leemann (SSC-16). These reports also appear as Appendices 5.2 and 5.3 of this report.

For the trim coils, the coupling between the dipole trims was considered as the worst case for the spool piece. The RDS trim coil design was not optimized for small coupling, but a variation in this design, with the dipole coil next to the beam pipe, gives a small coupling which can be decreased further by making the coil longer. Again, the problem is more easily solved for Designs B and D than it is for Designs A and C. However, it was concluded that a satisfactory solution could be found for any of the designs, the penalty being a small increase in cryogenic length.

6.2 Operations and maintenance cost

The Operations Cost Subgroup estimated that the yearly operations cost differential between a 3T and a 6T SSC would be about $20M (see Appendix 6.11). The estimates were based upon a model which assumed an 8 km spacing between collider satellite operating centers distributed about the ring. This distance was specified by the needs of refrigerator placement, cryogen flow specifications, power supply distribution and operations and maintenance center requirements. Manning and operating the extra centers required for the 3T machine accounted for about 3/4 of the cost differential, with the remainder due to somewhat larger power requirements for the 3T ring.

The possibility of doubling the spacing interval to 16 km was considered as a cost saving measure, especially for the 3 Tesla version. This increase in satellite center spacing was found to be unacceptable, mainly because of the cryogen distribution specifications and the uneasiness about emergency situation response times. In addition to these concerns, one found that the 3 Tesla design used twice the number of refrigerators, each half as large, and three times the number of guide field power supplies distributed about the ring, therefore requiring more centers and favoring an 8 km spacing interval. This spacing selection results in 12(6T) or 24(3T) satellite centers and thus differences in costs due to helium make-up, power consumption and number of shift personnel required to maintain the equipment in each center. We also considered whether there might be further penalties due to ring size. The major item was the difference in the size of the "tunnel rat" crews due to the logistics of increased distances and travel times for a larger circumference ring. This was corrected for the 40% fewer correction packages that require servicing in the 3 Tesla design.

In the context of this model and assuming minimal operating costs for the laboratory, the cost differential was slightly under 10% of the laboratory operating cost. The absolute difference of approximately $20M per year for the larger ring is considered to be more accurate than the percentage difference.

The operations cost subgroup also looked at the time and manpower requirements involved in changing a magnet after a magnet failure. (See Appendix 6.8.) Our estimate showed that the time from failure to re-establishment of beam was 4.7 days for the one-in-one 6 Tesla magnet, 5.4 days for the dual 6 Tesla magnet, and between 7.2 and 9.4 days for the 3 Tesla dual magnet. This is to be compared with the 3.4 day average for changing a Tevatron magnet and re-establishing physics operations.

Another topic investigated was the amount of "free" accelerator study time that would be made of one-in-one magnets. (See Appendix 6.9). Using the Tevatron downtime log as a data base, it was estimated that about 25% of the normally scheduled accelerator studies could be done while one ring was down for repair of one of its systems. Since about 20% of available beam time is typically devoted to accelerator experiments we therefore estimate a 5% bonus in increased high energy physics beam time.

6.3 Conclusions

The four most significant conclusions which emerge from these studies are:

1) There is a real difference in terms of operating cost and complexity between the very large 3T ring and the smaller 6T ring, at least as they are presently designed. The larger ring requires twice as many refrigerators, three times the RF and magnet power, twice the abort system capability, and twice as many stored protons. All of this leads to an additional operating cost of about $20M per year (just under 10% of the estimated annual operating cost) an additional staff of 146 (5.5% of the total estimated laboratory population) plus additional uncertainties associated with mobilization of personnel, to do maintenance and repair on the larger ring, and on the location and inventory of spare parts.

2) With magnet systems which are coupled either cryogenically or magnetically, both machines are off-line and require more downtime for magnet replacement when a magnet fails. Coupled systems are therefore less flexible in terms of initial installation, survey and subsequent alignment, commissioning, accelerator physics studies, return to service after a magnet replacement, and flexibility for subsequent physics programs. Also, the possibility of adding redundancy in the cryogenic system is enhanced by the one-in-one solution. The cryogenically coupled system is probably cheaper to build, but we were unable to discuss any significant operating cost penalty if the more flexible one-in-one system is selected.

3) The basic concept of a low field magnet system (less iron mass and consequently more rapid cool-down, lower field and mechanical forces, fewer problems at injection, fewer vacuum problems due to synchrotron radiation, fewer cold connections etc.) probably mean its magnet ring will require less repair once the basic reliability of the design is demonstrated during the in-depth design and system testing phases.

4) While the group debated and agonized over operational implications associated with magnet length, the number of cold power connections per system, the number of cryogenic connections, the number of vacuum connections etc., it was unable to develop any models that would indicate that one design had more overall reliability than the other, or to pursue any type of a failure mode effects analysis on the basis of models or Tevatron experience. Moreover, it was felt that most of the specific troublesome features of all designs would be eliminated in the design and system testing phases for the selected magnet system. Nevertheless, the group considers that the above three conclusions are more generic and will remain significant factors in the final choice of the magnetic field and magnet style to be selected in the SSC.

7. REPORT OF THE SYSTEMS GROUP

Introduction

The charge to the Systems Group of the Workshop was to rank the importance of each of the collider systems with respect to the problem of magnet type selection and to assign a grade as to how well the various magnet types satisfied these systems requirements. After some discussion, it was decided that the systems listed in Table 7-1 below were the most important ones to consider in this study. The quench detection and protection system and the magnet power supply system dominate the list since they are absolutely crucial to the successful operation of the collider. The ranking is based on a scale ranging from 0 (unimportant) to 10 (crucial).

Table 7-1

Collider Systems

System	Importance
Quench Protection	10
Magnet Power Supplies	8
Correction Elements	6
Vacuum	5
Beam Diagnostics	5
RF	5
Beam Stabilization	5
Controls	3
Complex Failure Modes	6

The other principal task of the group during the workshop was to agree on a schedule for the detailed work on the assessment of each of these systems, and to assign responsibility for completion of that work for inclusion in the final report of the task force. That detailed work has now been completed and the reports of this work are given in Appendix 7. The overall impression of the group after the detailed analyses has not changed from that reported in the workshop summary. There are no overwhelming reasons for selecting one magnet type based on systems considerations for commissioning and operating the SSC. Generally, each of the systems for the present 3T design with perhaps the exception of the quench protection system is more complex and as a result may have a higher operational cost and require more effort to successfully commission the collider.

The results of the more detailed analyses are briefly summarized in the following sections.

7.1 Quench detection and protection

About one third of the group's effort was devoted to analyzing the implications of the quench protection schemes for commissioning and operations, with particular attention to failure mechanisms. Appendix 7.1 gives a detailed discussion of the conclusions summarized below.

The straightforward analog quench detection system now planned for the 3T magnet was described to the committee, which then compared it with the Tevatron's successful microprocessor-based system. The detection scheme for the 3T magnet is illustrated in Fig. 7-1.

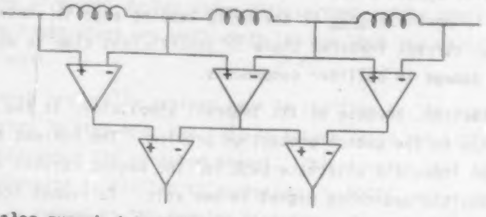

Fig. 7-1. Analog quench detection circuit (3T magnet).

Although the analog detection scheme illustrated above is conceptually simple, it must have high common-mode rejection, especially during upset conditions, and it is sensitive to amplifier input offsets. The microprocessor-based scheme avoids these problems and in addition provides the needed data base to determine the operational integrity of the system. The analog system would require a parallel digital system to monitor its performance. After correction of an initial software design flaw, the microprocessor-based system used for the Tevatron has been extremely reliable. The discussions illuminated one feature of passive quench protection systems using shunt diodes: the detection system must operate with threshold voltages for opening the shorting switches across the dump resistors of < 0.5 volt, compared to the < 10 volt level used in the active quench protection system. The measured noise levels in the Tevatron system are at the 0.1 volt level for a 50 Hz bandwidth, uncomfortably close to 0.5 volt. The quench detection and protection system must operate with an expected mean time between false quenchs per protected section of several years for reliable SSC operation. The 0.5 volt threshold is chosen so that it is below the one volt "on" voltage of high current Si diodes operating at room temperature. At 4.5°K, the initial "on" voltage in such diodes is approximately 4 volts, but it quickly drops to 1 volt because of the low heat capacity of the copper mounting block in conjunction with the high power level in the conducting diode. Because of this behavior, it may be possible to achieve better noise immunity by operating with the quench detection threshold set nearer 1 volt.

One idea proposed during the workshop was to sense the current flowing through the passive bypass diode in order to detect quenches with better noise immunity. This is possible only if the early leading edge is sensed, because after substantial current transfer there is insufficient time to abort the beams and avoid damage to collider components.

Passive protection, because of its inherent simplicity, is the most desirable solution to the quench protection problem. The current bypass diodes provide an immediate alternate path for the magnet current and limit the voltage across the quenching magnet to one volt. To remove the stored energy in the magnet string, dump resistors must be placed in series with the magnets to reduce the circuit time constant and absorb the energy. This is accomplished by opening shorting switches across these resistors. To minimize the heat load to 4.5°K the bypass diodes also should be at 4.5°K but their use in a reliable way requires considerable R&D on their failure rate in this mode of operation and on their radiation sensitivity, since they are located close to the beam. These diodes are substantial ones with peak current ratings of 10 kA. The consensus of the group is that passive quench protection would certainly work for the 3T magnet and that it probably could be made to work for the 5T and 6T magnets but would require many more diodes. Table 7-2 is a comparison of the parameters for passive quench protection for the three magnet types.

Table 7-2

Passive quench protection comparison (one sector = 1/12 of ring).

Item	3T(Fe)	5T	6T(Fe)
Power Supply	3 (Inner, Outer, Quad)	1	1 + Q-trim
Dumps/PS	2	4	4
Diodes (Cold)	320	1360	792
Time Constant (sec)	2.5	30	20
I_{max} (kA)	10	6	5.6

Because of potential diode reliability problems the group concluded that in the case of the 3T magnet design using high-current safety leads to place the diodes at room temperature was well worth the one watt per pair in 4.5°K refrigeration cost.

Active quench protection systems have in addition to the bypass diodes a system of heaters located near the coil to insure rapid and uniform quench propagation throughout the quenched magnet. This insures that the temperature rise in the conductor is limited to approximately 500°K, while most of the stored energy is dumped in the dumping resistors. The thermal time lag determines the energy deposited in the initial normal region and requires that the heaters be fired in the shortest possible time after the detection of a quench. Because the protection is active, the current bypass diode can be replaced by an SCR, which may have some reliability advantages. By using active protection the number of bypass diodes can be substantially reduced and safety leads can be used to place the active components at room temperature. Table 7-3 summarizes the component count for the two high-field magnet types used in the Reference Designs.

Table 7-3

Active quench protection comparison (one sector = 1/12 of ring).

Item	5T	6T(Fe)
Heater Power Supply	160	288
Bypass SCR/Diode + Cable	160	288

The conclusion of the group was that the passive system was simpler and hence probably more reliable from an operational point of view. It was noted, however, that the active quench protection system used on the Tevatron accounted for less than 3% of the downtime of that accelerator. With either system, substantial design effort must be devoted to providing a thorough and efficient checking system, to be used at the beginning of every ramp cycle to insure the proper functionality of the system. It must work!

7.2 Power supplies

As with the quench protection system, about one third of the effort of the group was devoted to analysis of the magnet power supply system. After discussions with our colleagues in the design group and listening to our CERN colleagues describe their operating experience with S$\bar{p}$pS collider, it became clear that the tracking between the quadrupole and dipole magnet currents must be within a few parts in 10^5. The requirement that the betatron tune spread be < 0.002 during acceleration to limit particle loss, and during colliding beam operation to limit emittance growth, implies current regulation with $dI/I < 2 \times 10^{-5}$ for the SSC. At first sight this requirement seems to provide an interesting design challenge, because the Reference Designs used 12 separate power supplies coupled together by differential transductors to provide the dipole and quadrupole magnet current. Assuming that the current errors are random, each power supply must then regulate to a factor of

$12^{1/2} \sim 3.5$ better than the overall regulation requirement. The cumulative effect of these random errors may be avoided by connecting the entire ring in series, with 12 equally spaced power supplies, all except one operating in the voltage control mode, with the remaining one operating in the current regulation mode to close the current regulation loop. For the ramp rates specified in the Reference Designs the total power supply voltage requirement is less than 1360 volts for Design A (and D) and 270 volts for Design C (in both cases plus power lead drops), which is easily satisfied. Because of the four-volt "on" voltage for cold diodes, substantially higher voltage at low output currents may be required to test the integrity of a passive quench protection system. The single-loop solution has the penalty of requiring at least 12 high current active and fast switches as in the Tevatron power supply system, which must act reliably during upset conditions, in order to limit voltage to ground by isolating the faulty sector from the circuit. Commissioning may be more difficult because the entire magnet is in series.

Lyn Evans from CERN described the S$\bar{p}$pS magnet power supply regulation requirements during a talk on overall performance of the collider. Because of intrabeam scattering they must limit the tune-spread contribution from the power supply system to less than 0.001, which implies an overall current regulation to better than 3×10^{-5}. The magnet power supply system uses separate power supplies for the vertically focusing quadrupoles, the horizontally focusing quadrupoles, and the dipoles. Within a factor of two, they are achieving the required SSC regulation accuracy during normal operation.

To limit the sextupole contribution to an acceptable level in the 3T magnet, the eight-turn main coil is separated into two separate circuits (inner and outer), and a single-turn separate correction winding requiring about one third the main current has been added. The currents in the two sections along with the decapole correction winding current necessary to achieve the required decapole tolerance are shown in Fig. 7-2 as a function of the dipole field. Only the sum of the two currents from the two power supplies (I_{inner}) has to be regulated to the level mentioned above, with the tolerance on the ratio being at the part in a thousand level. The correction winding current must be regulated to a part in 10^4. The quadrupole magnets are on a separate power

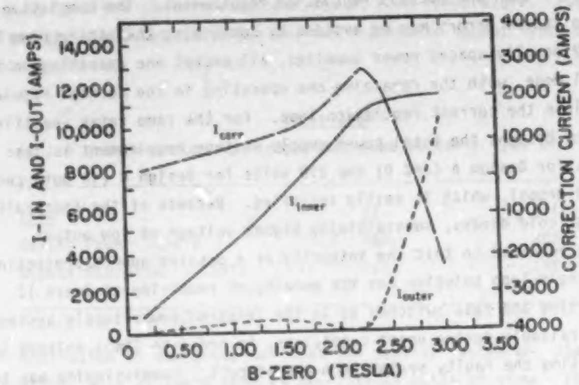

Fig. 7-2. I_{inner}, I_{outer}, and I_{corr} vs. Magnetic Field for the 3T Magnet

supply and require 3 kA at the peak collider energy; this supply must be regulated to a part in 10^5.

A feature of magnet power supply systems which has often been overlooked (with painful consequences) is the transmission-line behavior of the magnet inductance and the shunt capacitance of the coil to ground. The cutoff frequency of these lines can be in excess of several tens of kHz. One of the problems in commissioning the S$\bar{p}$pS collider was a dramatic sensitivity to switching noise spikes from the power supply which caused field spikes at the milligauss level driving the first betatron resonance at 12 kHz. The SpS magnet as a transmission line cuts off at 50 kHz, so the noise spikes were being transmitted without attenuation by the magnet system. Installation of a low pass filter on the power supply output which eliminated these spikes improved the luminosity lifetime by 30%. A first pass analysis of transmission line effects in the SSC magnet types is given in Appendix 7.3. Propagation of signals by the line can be damped simply by including a shunt resistance across the magnet at each quench protection bypass diode. However, these resistors pose a commissioning and operational difficulty when measuring coil leakage. Although it may be simpler to provide well filtered power supplies, the shunt resistors are probably necessary in any case to improve the transient response of the magnet circuit to assure the necessary current regulation during ramping.

In comparing power supply requirements for the various magnet types, the group concluded that inductive coupling was probably the most important aspect. One-in-one designs received the highest marks since they are completely isolated. Transformer coupling into the other current loop during upset conditions imposes more stringent design criteria on the power supply system, and will make the system more complex and hence less reliable. Because the 3T magnet has three separate coils which are magnetically coupled, it is at least a two-in-one magnet from the power supply point of view.

7.3 Magnetic correction elements

The main distinction between the high field (5T and 6T) magnets and the low field (3T) magnets with respect to the required compliment of correction elements lies with the requirement of distributed sextupole correctors. Due to persistent current effects in high field magnets, one must compensate for the sextupole field in the dipoles at injection energies. Each dipole magnet must have a sextupole winding which is then connected in series with similar windings on the other dipole magnets in a cryogenic loop in a sector (2 circuits/bore/sector = 4 circuits per sector). This extra winding provides another form of magnetic coupling, and hence undesirable design complications and decreased reliability. Otherwise, the comparison between the different magnet types is just a straightforward numerical one with the high field designs having approximately 10% fewer correction elements compared to low field ones. The number of separate power circuits is approximately the same.

7.4 Vacuum system

The obvious differences between between the 3T and the 6T magnet design vacuum system are the length of the physical system and the cross section of the beam tube. The 3T design has a beam tube with an elliptical cross section with a height of 2.42 cm and a width of 3.48 cm, while the 6T design has a circular cross section with inner diameter of 3.30 cm. In addition, the distance between pump down ports is 140 meters for the 3T design, while it is 100 meters for the 6T design (assuming that the pump-down ports are located only at the correction element packages). The principal difference is in the likely operating base pressure due to the different gas desorption rates driven by the synchrotron radiation power levels in the two designs. The relevant scaling relationships for fixed beam current are

$$\text{Synchrotron radiated power/meter} = \text{const.} \times B^2 \times E^2$$

$$\text{Number of radiated photons/meter/sec.} = \text{const.} \times B \quad .$$

The critical energy, $U_c = 3hc\gamma^3/4\pi\rho$, (conventional definition = 1/2 of Jackson's definition) for the 3T design is 129 eV, and for the 6T design 258 eV. Since these energies are large compared to the typical binding energies (~1 eV) of adsorbed gas molecules to metal surfaces, it is probably the photon number flux that will determine the operating pressure. The base pressure will only depend on the number of protons per bunch and the bunch spacing since the circulation time around the machine (330 μs or 660 μs for the 6T or 3T design respectively) is long compared to the transit time for a molecule with greater than 0.001 eV kinetic energy. A 0.001 eV kinetic energy H_2O molecule has a velocity of 1.03×10^4 cm/s. The thermal energy of a molecule at 4.2°K is approximately 0.0003 eV, so its velocity is about 5.7×10^3 cm/s.

7.4.1 Beam tube pumpdown time (commissioning)

The pumpdown time during commissioning and after a magnet replacement is determined solely by the outgassing rate of the inner surface of the beam tube and the pumping speed of the beam tube. Assuming no leaks, the base pressure achieved during this room-temperature pumpdown determines the total adsorbed gas inventory and will thus determine the operating pressure during colliding beam operation, when the beam tube is at 4.2°K. The steady state solution for the pressure in a pipe being pumped from one end and closed at the other, with a distributed gas load due to outgassing, is straightforward and given in Appendix 7.3. The pressure along the pipe is given by

$$P_x - P_0 = QB[(x/C) - x^2/(2CL)]$$

where P_0 is the pressure at the pump end of the pipe (x = 0) and P_x is the pressure at the point x, Q is the outgassing rate of the surface (in

Torr-liters $s^{-1}cm^{-2}$), B is the cross-section perimeter, and C is the conductance (in liters s^{-1}) of the pipe. The maximum pressure is at the closed end of the pipe with a value given by

$$P_L = QBL/(2C)$$

where the pump pressure has been neglected. Q is of course a function of the surface treatment and the material and has a time dependence which can be represented after some short initial time t_o (typically 1 h) by

$$Q = Q_o\ (t_o/t)^{\alpha}$$

where Q_o is the outgassing rate at t_o and $\alpha = 1$ for most metals. Table 7-4 summarizes the maximum pressure as calculated for the 3T and 6T designs after 24 hours of pumping assuming $Q_o = 3 \times 10^{-9}$ Torr-liters $s^{-1}cm^{-2}$ (mostly H_2O) which is characteristic of clean, degreased stainless steel or copper.

Table 7-4

Maximum beam tube pressure (24 hr.).

Magnet	Beam Tube Radius (cm)	Pump Separation (m)	Conductance (liters/sec)	P_{max}(Torr)
3T	1.21 x 1.75	140	0.041	10×10^{-5}
6T	1.65	100	0.087	3.7×10^{-5}

The average pressure along the beam tube is 2/3 of the maximum pressure, or 6.7×10^{-5} Torr for the 3T design and 2.4×10^{-5} Torr for the 6T design. These average pressures plus the several adsorbed monolayers correspond to substantial gas loads in the beam tube vacuum system.

7.4.2 Operating pressure

The operating pressure is the result of a complicated interplay between the gas load due to the slow pumping speed of the beam tube itself, the number of synchrotron radiation photons striking the surface per second per meter, and the long term molecular composition of the residual gas in the beam tube due to breakup of the original molecules by the energetic photons. The latter remark is particularly significant if H_2O eventually becomes H_2, which is difficult to cryopump because of its relatively high vapor pressure. Additional important experimental information will be forthcoming from the desorption experiments being carried out at the Brookhaven National Synchrotron Light Source during the next few months, which will determine the gas evolution rates from cryopumped Cu surfaces illuminated by photons in this energy region. As part of these tests, it is important to measure the molecular composition in low pumping speed environment as a function of time to see if molecular breakup is an important aspect of the beam tube operating pressure. The final answer must await these test results and further analysis. It is already clear, however, that a substantially more elaborate pumping scheme will be required than is now envisioned, to provide much greater pumping speed during commissioning and magnet replacement to reduce the gas load to an acceptible level. Both theoretical analysis and $S\bar{p}pS$ experience indicate that an operating pressure of less than 10^{-9} Torr is necessary to assure adequate beam lifetimes.

7.5 RF system and beam stabilization

In the Reference Designs for the high field magnets (5T and 6T), the 20 MV accelerating voltage provided by the 356 MHz RF system gives the necessary overvoltage for stability against intra-beam scattering during full energy operation, and permits acceleration at a constant ramp rate in 1000s. It is also sufficient for control of the transverse node-coupling instabilities during injection.

While 20 MV seems sufficient for full-energy operation of the 3T machine, it is insufficient during injection. As discussed in Section 5 and Appendix 7.5, the required voltage scales as Z_T^2C, where Z_T is the transverse impedance and C the machine circumference. The transverse impedance is about twice as large, mostly because of the smaller beam tube. As a result, a factor of 8 more RF voltage is required during injection than in the high-field case. The average power is the same (Appendix 7.5), but the RF system is larger by a factor of four, and hence is more expensive, less reliable, and somewhat more difficult to commission.

The longitudinal and transverse feedback systems necessary for beam
stabilization are essentially equivalent for all magnet types, with a slightly
more powerful transverse system required for the 3T design.

7.6 Beam position and loss monitoring

An appropriate assessment of the impact of magnet type on the beam
position and beam loss monitoring systems must await a detailed design for
uadrupole ends and correction element packages, which are now at a very early
evelopment stage. It is the consensus of this group that these systems
hould be as well instrumented as possible, with wide dynamic range and, as a
ery minimum, provide a measurement of both beam position coordinates at every
uadrupole. An analysis by R. Schafer, which is referred to in Appendix 7.6,
ndicates that both beam position coordinates can be measured in the same
ength along the beam line as used by the single coordinate measurement pro-
osed in the Reference Designs Study. The power deposited in these electrodes
the beam is dissipated at room temperature and thus the only 4.5°K heat
ad is from the electrical leads.

7 Complex failure mode analysis

The recent failure of a 13 kV power transformer providing power to the
vatron magnet power supply, which resulted in the destruction of 5 Tevatron
gnets by high voltage breakdown, dramatically illustrates the importance of
s topic. Although complex failure events have little leverage in determing
SSC magnet selection, it is important to continually mention this topic to
ure the successful operation of the SSC. This is especially true in a
uation where a very complex machine will be designed by a large team of
igners each carefully insuring that their particular subsystem will survive
conceivable event with little attention to the interaction of their pro-
tive circuitry with that of others. It is entirely possible to build a
ine that you can not turn on because of the failure probability of the
mal interlocks on the 5 volt logic power supplies for the tunnel data
isition system.

7.8 Conclusions

After detailed analyses of the implications of the various magnet types on the system aspects of commissioning and operating the SSC, the conclusion of the Systems Group is that there is no strong signal to aid in the magnet selection. The differences are at the 5% level and therefore are probably in the noise at this stage of the design. Generally, the 3T systems are more complex, and as a result are perhaps less reliable. In the case of the magnet power supply system, the four high current circuits dissipate substantial power in necessary room temperature components. The present beam tube vacuum system, as presently designed, is inadequate in all proposed magnet designs.

Appendix 1

PARTICIPANTS IN THE WORKSHOP ON COMMISSIONING AND OPERATING THE SSC, UC BERKELEY, 1985 January 14-18

Workshop Coordination

Don Groom	University of Utah
Peter Limon	Central Design Group
Karen Larsen	Lawrence Berkeley Laboratory

Cryogenics Group

William Fowler, Coordinator	Fermi National Accelerator Laboratory
Donald Brown	Brookhaven National Laboratory
Claus Rode	Fermi National Accelerator Laboratory
Peter VanderArend	Cryogenics Consultants, Inc.
John Van Sloan	Air Products & Chemicals, Inc.
Richard Wolgast	Lawrence Berkeley Laboratory

Design Group

Christoph Leemann, Coordinator	Lawrence Berkeley Laboratory
Alex Chao	Central Design Group--SSC
Ernest Courant	Brookhaven National Laboratory
Don Edwards	Fermi National Accelerator Laboratory
Eugene Fisk	Fermi National Accelerator Laboratory
Albert Hoffman	Stanford Linear Accelerator Center
Steve Peggs	Central Design Group--SSC
Jack Peterson	Lawrence Berkeley Laboratory

Operations Group

Paul Reardon, Coordinator	Brookhaven National Laboratory
Phil Bryant	CERN
Lyn Evans	CERN
Mike Harrison	Fermi National Accelerator Laboratory
Russ Huson	Texas Accelerator Center
Andrew Hutton	Stanford Linear Accelerator Center
Derek Lowenstein	Brookhaven National Laboratory
Robert Mau	Fermi National Accelerator Laboratory
Rich Orr	Fermi National Accelerator Laboratory
John Poole	CERN
Luc Vos	CERN
Peter Wanderer	Brookhaven National Laboratory

Systems Group

Donald Hartill, Coordinator	Cornell University
Dixon Bogert	Fermi National Accelerator Laboratory
Richard Cassel	Stanford Linear Accelerator Center
Karl Koepke	Fermi National Accelerator Laboratory
Gerry Tool	Fermi National Accelerator Laboratory
Peter Yamin	Department of Energy
John Ziegler	Texas Accelerator Center

Appendix 2

AGENDA OF THE WORKSHOP ON COMMISSIONING AND OPERATIONS OF THE SSC

UC Berkeley, 1985 January 14-18

Monday 15 January

08:30-10:30	Introductory talks. 1. Peter Limon (SSC/CDG): Welcome, Organization, and Work Assignments 2. Ewan Paterson (SLAC): "SLAC Reliability Experience as Applied to the SSC." 3. Mike Harrison (FNAL): "Aperture Requirements Imposed by Operational Considerations." 4. Peter VanderArend (CCI): "Cryogenics Problems of SSC Magnets."
10:30-12:30	Organizational meeting of taskforce groups.
13:30-17:00	Individual and group work; continued organizational meetings.

Tuesday 15 January through Thursday 17 January

Each of these "main workdays" had the same schedule.

08:30-09:30	"News Reports," in which the coordinators of each group gave 15 minute reports of progress to date and plans for the immediate future.
10:30-12:30; 13:30-17:00	Individual and group work. However, individual group meetings were held at non-overlapping time, in which talks announced at the morning "news conferences" were given.

In the course of the three days, the following talks were presented:

Tuesday 15 January

1. Cryogenics: 11:00 a.m.

   Claus Rode: "SSC Magnet Cryogenic Comparison (Design A, B, C, & D) Impact of Common Failures."

2. Operations: 1:30 p.m.

   Bob Mau: "Commissioning the FNAL Energy Doubler."

   John Poole "SSC Warm Start Time Estimate."

   Phil Bryant: "Magnetic Coupling Effects at the ISSR."

4. Systems 4:00 p.m.

Karl Koepke: "Quench Detection and Protection of SSC Magnet Systems."

Wednesday 16 January:

1. Cryogenics 11:00 a.m.

John Van Sloan: "Commissioning a Large LHe Plant."
Don Brown: "Cryogenic System Performance Assumptions."

2. Operations 1:30 p.m.

Russ Huson: "Status of TAC"
Derek Lowenstein: "Operations Cost Subgroup Report."
Rich Orr: "Magnet Change Time Estimates."
John Poole: "2-in-1 vs 1-in-1 Commissioning and Operation Considerations."

4. Systems: 4:00 p.m.

Richard Cassel: "Power Supply Regulation."

Thursday 17 January:

3. Design: 2:45 p.m.

Lyn Evans: "The SppS."
Ernest Courant: "Consequences of 3 Tesla Versus 6 Tesla."

Friday 18 January:

08:00-12:00

Reports of the working groups. (These included tentative results obtained during the Workshop, and schedules of work to be completed by meeting of the Taskforce, scheduled for 26 February, 26 March, and 15 April.)

Appendix 3

MAGNET DESIGNS AS OF 1985 JANUARY

The four designs considered were:

1. Evolved Reference Design A. Although there is no current development of this two-in-one concept, the magnet had evolved to consist of stainless-steel collared coils in a cold iron yoke, as shown in the Fig. A3-1. The coil inner diameter remained at 4 cm, with a 3.3 cm beam pipe inner diameter. At high field most of the flux goes through both bores, due to the side-by-side configuration.
2. Reference Design B. (Fig. A3-2) No substantive change has been made since the reference design report. Design B is a collared coil one-in-one 5T design, with complete independence of the two rings. The coils are based upon the Tevatron magnet design. Magnetic isolation of the rings is provided by warm iron which also serves as the vacuum enclosure. The bore orientation can be either over-under or side-by-side.
3. Evolved Reference Design C. (Fig. A3-3) While this design has evolved considerably since the Reference Design Report, overall dimensions and performance characteristics remain approximately the same. The two bores are coupled cryogenically but are expected to show very little magnetic coupling. Strong preference for an over-under design is imposed by mechanical considerations: The over-under arrangement is quite stiff in the vertical direction, requiring relatively infrequent support points with their consequent cost and heat loss. The extremely long magnets are to be deformed into position, slightly bending them in a direction along which they have little rigidity.
4. Design D. (Fig. A3-4) This 6T design is in essence a one-in-one version of the evolved Type A magnet, and also contains the best features of Design B. It consists of a stainless-steel collared coil with a 4 cm bore in the center of a 27.6 cm diameter cold iron yoke. Suspension in the cryostat, provision for helium flow around the beam

pipe, and other details, are similar to those of the Type A two-in-one design. The two rings are independent, and the relative bore orientation is arbitrary.

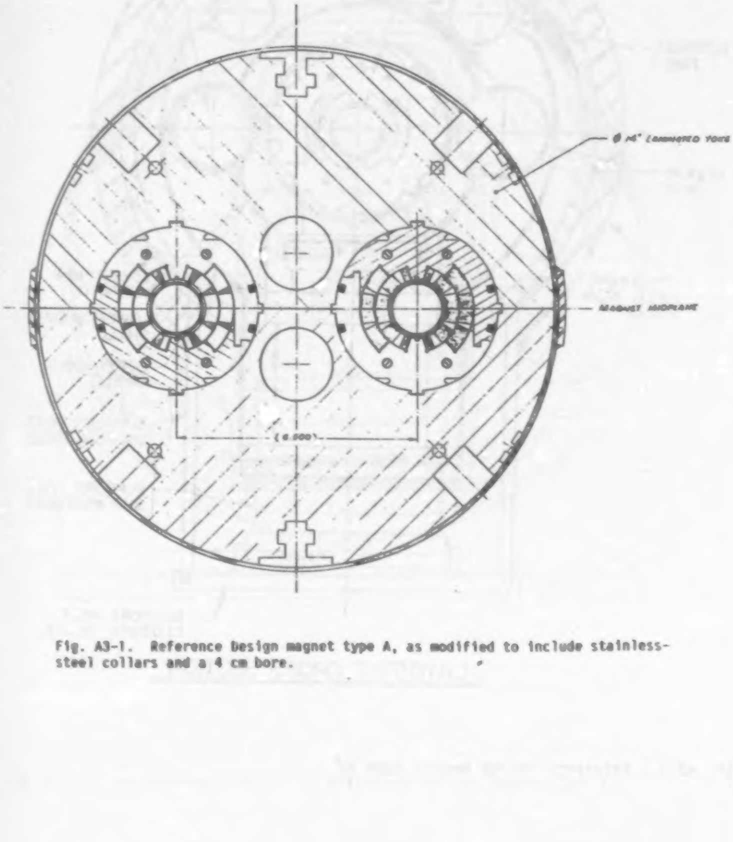
⌀ 14" LAMINATED YOKE
MAGNET MIDPLANE
(6.500)

Fig. A3-1. Reference Design magnet type A, as modified to include stainless-steel collars and a 4 cm bore.

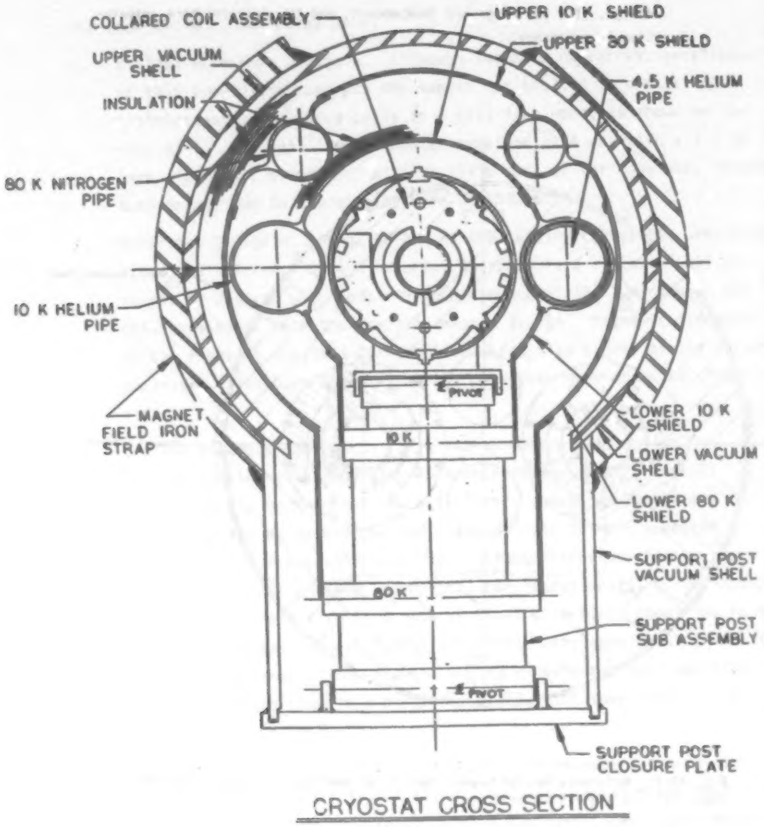
COLLARED COIL ASSEMBLY
UPPER 10 K SHIELD
UPPER 80 K SHIELD
UPPER VACUUM SHELL
4.5 K HELIUM PIPE
INSULATION
80 K NITROGEN PIPE
10 K HELIUM PIPE
℄ PIVOT
10 K
MAGNET FIELD IRON STRAP
LOWER 10 K SHIELD
LOWER VACUUM SHELL
LOWER 80 K SHIELD
SUPPORT POST VACUUM SHELL
80 K
SUPPORT POST SUB ASSEMBLY
℄ PIVOT
SUPPORT POST CLOSURE PLATE
CRYOSTAT CROSS SECTION

Fig. A3-2. Reference Design magnet type B.

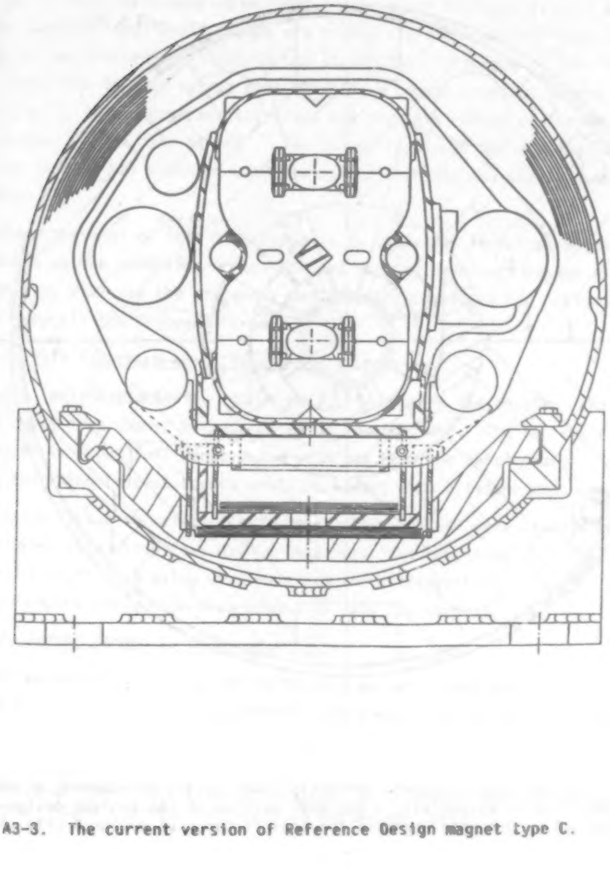

Fig. A3-3. The current version of Reference Design magnet type C.

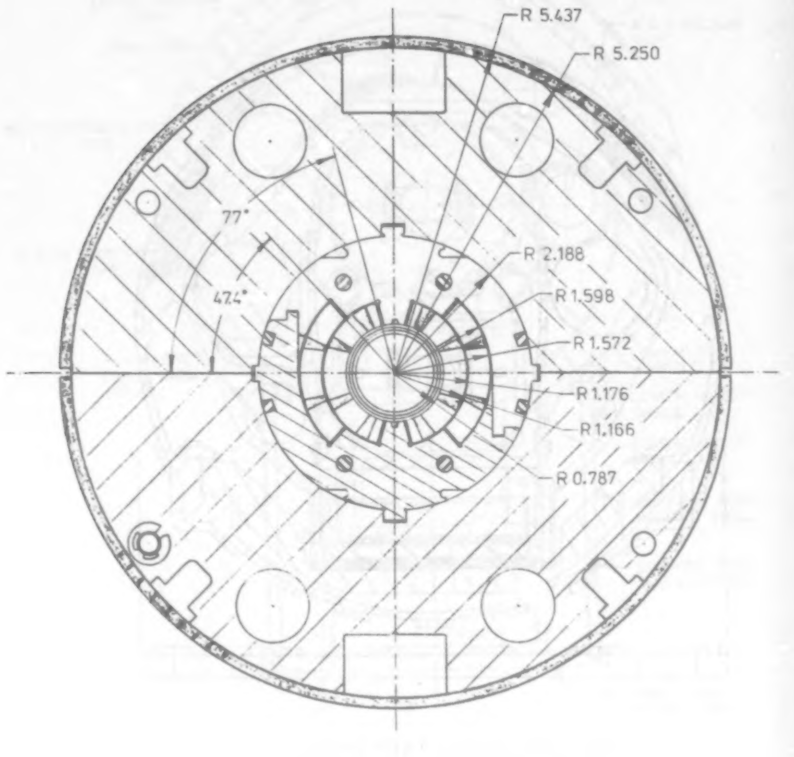
R 5.437
R 5.250
77°
47.4°
R 2.188
R 1.598
R 1.572
R 1.176
R 1.166
R 0.787

Fig. A3-4. The new type D magnet, currently under active development at LBL, FNAL, and BNL. It is essentially a one-bore version of the evolved design A, shown in Fig. A3-1, but also contains the best features of design B (Fig. A3-2).

Appendix 4.1

LARGE SCALE WARMUP AND COOLDOWN

Introduction

In this report we will deal with the eight magnet types shown in Fig. 4.1-1; the corresponding parameters are given in Table 4.1-1. While the "Cryo. Coupled" and "Dual" magnet are highly different magnets they numerically can be treated equally from the standpoint of cooldown. The "Dual" differs from "one-in-one" except that there is a common cryostat, where each is structurally independent and therefore has the same number of supports, helium pipes, etc. as the "one-in-one". The "Cryo. Coupled," while being mechanically much stiffer has problems with bowing and high thermal stresses during cooldown.

Since the goal of this task force is to study the impact of magnet selection on the operation of the SSC and not the reference design cryogenic systems, we will use the cryogenic design being developed for Design "D" jointly by all the Cryogenic Groups.

A4.1.1 Full ring warm up to room temperature

This "unlikely activity" occurred last summer at the Tevatron and will occur again next summer because of civil construction. The SSC could be warmed up in about four weeks using warm gas from the refrigerators. The areas requiring fastest access would be warmed with a faster procedure.

For the Tevatron warmup, last summer, five houses* were warmed in the first three days using "one day" procedures. The remaining 21 houses were warmed in eight days using warm gas from the refrigerators. In reality the fast procedure would have been needed in only two houses.

A4.1.2 Sector warmup to room temperature

The warmup of a full sector using warm gas will take nearly as long as the full ring. If electric warmup heaters are used, a sector can be warmed up in

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*The Tevatron is divided into six sectors, as is the SSC in the reference designs. There are four refrigerator houses per sector.

$$\Delta\epsilon = \frac{1}{\beta^*}\left[\frac{2}{\pi k}\,\theta L\,\frac{\sin(N\pi\delta)}{2\pi\delta}\right]^2 \tag{10}$$

The emittance growth needs to be much less than the natural emittance of the beam.

In this model, the driven beam moves collectively. A feedback system can thus in principle be used to damp the emittance growth. More will be said about this in the discussion section.

3. Numerical calculations

A simulation program has been written to simulate the overlap knockout resonance effects. The numbers used are

beam separation $r = 5$ mm
$L = 97.5$ m
$d = 15$ m
$\theta = 0.8\times10^{-8}$ rad
number of passages $N = 10000$, or the nearest number for maximum $\Delta\epsilon$

The distance L is chosen such that it is an integral multiple of d/2, and the analytical calculation of the previous section applies.

Figure 1 shows the emittance growth as a function of the tune ν in the neighborhood of $\nu = 84$, which is a multiple of 6. As expected, the resonances are spaced 0.004 apart. A closer inspection shows that the behavior near the resonances agrees very well with the expected (Eqn. (10)).

Figure 2 shows what happens if L is changed to 100.1 m. The sawtooth modulation no longer holds. The Fourier decomposition is then different from Eqn. (5). In particular, the higher order sidebands no longer become weaker as the resonance order increases in the simple way as Figure 1 shows. Nevertheless, the resonance strengths are basically the same.

Note that the tails of resonance are not negligible. If the tune is chosen to be in the range shown in Figures 1 and 2, for example, the emittance growth even "away from" resonances is larger than the natural beam emittance at 1 Tev (1×10^{-9}m).

4. Discussion

We have made an attempt to study quantitatively the strength of the overlap knockout resonances. We found that these resonances are closely spaced (0.004 spacing in tune units). If uncorrected, there will be intolerable emittance growth if the tune is close to a multiple of 6. By choosing the tune far enough away from 84 so that we are dealing only with very high order sidebands, however, the resonance strengths decrease algebraically. The background emittance growth "away from" resonances will at least become acceptable. In addition, the resonances are weak enough that perhaps a wide-band feedback system can cure most of the problem. The needed strength is of the order of a few gauss-meter.

We have not exhausted the study in this note. In particular, there are a few unanswered questions, as listed below:

1. We have not studied the effects of a betatron tune spread. The tune spread can in fact easily be wider than the resonance spacing of 0.004.
2. During operation, there may be a need to cross a large number of these resonances. If the resonances are caused by the different energies of the two beams, resonance crossings will occur when the lower energy beam is accelerated. This effect has also not been studied.
3. We have studied only a dipole motion of the driven beam. The higher modes are also driven by the overlap knockout mechanism. Although the strengths will be much weaker, they cannot be easily damped by feedback.

We would like to thank Steve Myers and Jack Peterson for useful discussions.

READEX FICHE

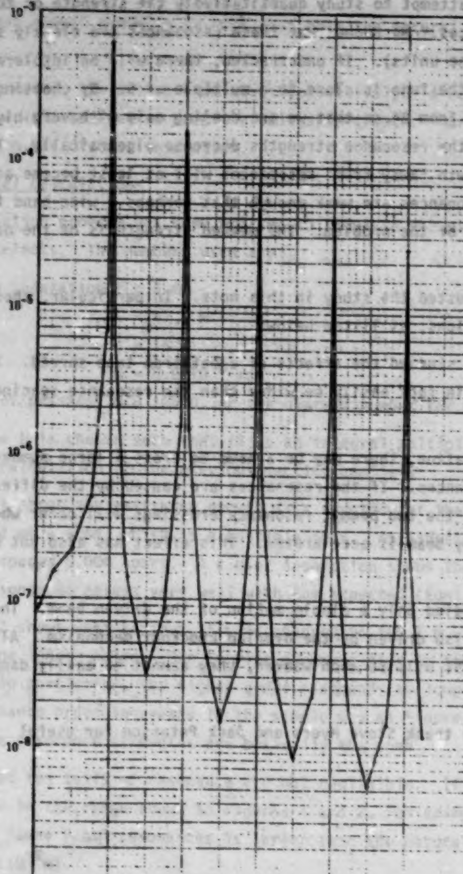

Fig. 1. The effective emittance growth due to overlap knockout resonance effects as a function of tune (ν) near ν = 84, for L = 97.4 m (= 13 d/2).

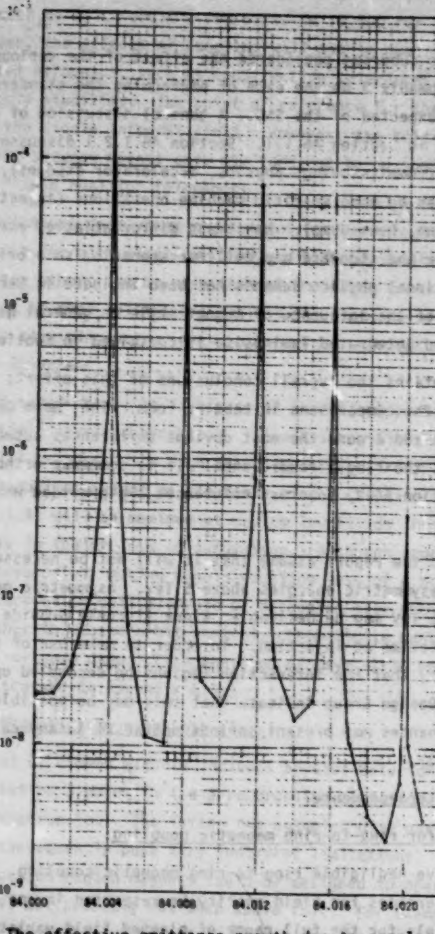

Fig. 2. The effective emittance growth due to overlap knockout resonance effects as a function of tune (ν) near ν = 84, for L = 100.1 m (= 13.35 d/2).

Appendix 6.1
BEAM GYMNASTICS

Introduction

The beam gymnastics subgroup considered the effect of the various magnet styles described in Appendix 3 on the ease of performing the standard beam gymnastics operations expected of the SSC. A general discussion of ring-to-ring coupling is given in Section A6.1.1. Section A6.1.2.1 discusses the SSC tasks in general form (commissioning, physics, accelerator studies), whereas Section A6.1.2.2 focuses on more specific machine operations (injection, acceleration, collisions, beam dump). No strong differentiation emerged from these comparisons under the standard p-p collider scenario, so a brief survey of the impact of additional physics demands has been included in Section A6.1.3. A discussion of the influence of magnet style on general qualities such as reliability and integrated luminosity is contained in Section A6.1.4.

Section A6.1.5 contains the overall conclusions of this effort; it also contains a summary of the comparisons in tabular form. The "Beam Gymnastics Issues" table is organized around the most obvious differences between the magnet styles, such as the ring circumference. It is somewhat orthogonal to the discussion in Section A6.2, so cross references are provided where appropriate.

The discussions in the report assume that it will not be necessary to operate the SSC with asymmetric energies above 5 TeV. Asymmetric operation in the range 1 TeV - 5 TeV may be desirable, since it could provide a safety factor in the beam lifetime at injection. In order to make use of this flexibility, it is necessary that the interaction regions be decoupled up to 5 TeV. Discussions with the Design Group indicate that this may be possible, but that overlap knockout resonances may present serious obstacles in any case (see Appendices 5.2 and 5.3).

A6.1.1 Sources of Interdependence.

A6.1.1.1 Tolerances for ring-to-ring magnetic coupling.

The goal is to have negligible ring-to-ring magnetic coupling. This requires that the tolerances for field quality be respected in one beam aperture at all field levels for the full range of planned field variations in the other. The field quality tolerances, although not yet specified in detail, are expected to be of order a few parts in 10,000 for dipole uniformity. To first order, the effects of coupling will add in quadrature with other sources of unwanted harmonics, such as construction tolerances, alignment errors, and power supply stability. The point of reference for the field quality tolerances is the dipole integral field. However, the tolerance for harmonics due to coupling between magnet ends may turn out to be somewhat tighter than the standard "field quality" tolerances.

An additional decoupling requirement has been found in ISR operations: Coupling via the main dipole or quadrupole field should not shift the closed orbit in the other ring by more than ±1 mm. This constraint arises from the requirement to keep collimators against the beams to protect physics experiments when adjusting beams in the other ring. For SSC, this might well be even more important.

As was noted above, it is essential that coupling be checked at all possible field level combinations. Direct stray field coupling (Section A6.1.3) will be worst with high field (saturated iron) in one aperture, when making the maximum change in the other ring. Coupling by permeability variations (A6.1.4) will be maximum at medium low fields in the test aperture when the iron is in the process of saturating. Although equal energy operation is assumed above 5 TeV, making dipole coupling less of a problem, it is necessary that all correction coil elements be uncoupled over their full range of operation, whether in closed orbit control, chromaticity control, tune control, injection, or beam dump. (The question of asymmetric operation above 5 TeV is briefly discussed in Appendix 6.5.)

A6.1.1.2 Magnets common to both rings

The list of common magnets includes physics detector magnets, some of the beam combination dipoles in the zero-crossing-angle schemes, and the low-beta insertion quadrupoles. The latter two examples give particularly tight coupling and consequently pose very important limitations. It was assumed that the intersection region magnets could be designed to operate independently below 5 TeV, but probably not much above that. For example, the low-beta quadrupoles might be turned off, and insertion dipoles decoupled via septa.

A6.1.1.3 Stray fields

Stray fields can affect the beams directly or by changing the reluctance of the iron return path. In this subsection we focus on field lines leaking directly into the other bore; in the next, on their causing changes in reluctance, and hence indirectly changing the field in the other bore.

A6.1.1.3.1 Dipole field body coupling.

In Reference Design A magnets at full field, the flux in one bore is returned through the other bore and the two rings are totally coupled. However, at low excitation, there is sufficient iron return path so that the rings are nearly uncoupled. At low field, coupling is indicated by the presence of harmonics which are unallowed by normal dipole symmetry, the quadrupole and the octupole. Gupta has calculated the change in harmonics that occurs if the two rings are at 1 TeV and 5 TeV instead of both at 5 TeV. For the quadrupole it is 0.35 units and for the octupole it is 0.41 units, where the units refer to the usual definition, a part in 10000 at 1 cm. The change in the allowed harmonics is much smaller, 0.16 units for the sextupole and 0.07 for the decapole. Qualitatively, then, Ref. Design A is satisfactory for asymmetric energy operation up to 5 TeV.

For Ref. Design B magnets in a common cryostat ("dual"), no detailed calculations of the coupling have been made. In this case there may be some concern about coupling at high excitation because of the relatively small distance between the iron yokes and the 0.4 T stray field at the surface of the iron. For low excitation (up to 5 TeV) the iron return path is generous and coupling is negligible.

The yoke for Ref. Design C magnets has been designed so that there should not be strong coupling between the two bores at any excitation. Pissanetzky has calculated the coupling for the two-current version of this magnet and found that the field seen by the other bore is a few tenths of a unit for a 1 TeV - 5 TeV unbalance. The result is expected to be little different for the three-current version of this magnet. This level of coupling was felt to be acceptable. (A qualitative discussion of coupling at high excitation for superferric magnets is given in the next section.)

The separation between the rings for the one-in-one version of Ref. Design A (Design D) is at least 61 cm, large enough so that only negligible coupling is expected. A calculation of the coupling by Snowdon and Oleksiuk confirms this (Appendix 6.6).

In all of the above, it can be assumed that if the dipole coupling is satisfactory, the corresponding quadrupole coupling is also satisfactory.

A6.1.1.3.2 Stray fields from dipole magnet ends

The effects of coupling due to magnet ends is experienced in the operation of the Fermilab Main Ring, which sees pronounced effects from the Tevatron magnets (Appendix 6.2). As a result, the Main Ring control programs must take into account whether or not the Tevatron is on. As in the case of the Tevatron dipoles, SSC cosθ magnet designs do not extend the iron yoke beyond the dipole straight section in order to avoid a peak field limitation in the ends. Thus, the question of stray fields from the ends is an important one. Detailed calculations are lacking in all the designs, so only a qualitative discussion is possible in this report.

In the current design of the ends of the superferric magnets, the ends are covered with iron which has a larger gap than the iron used in the straight section of the magnet. This increased reluctance reduces the field seen by the conductor and the stray field. Thus, coupling of the end fields to the adjacent bore is less than the coupling of the main field, which is satisfactory.

Snowdon has calculated the coupling due to stray field from a constant-perimeter end of magnets similar to Type D, using the program GFUN (Appendix 6.6). He finds less than 0.1 unit of dipole coupling and less than 0.01 unit in higher multipoles, a negligible level.

If the end harmonics in any of the magnets are found to be too large, a reduction can be made by extending the iron yoke to include the ends. For cosθ magnets, this typically reduces the peak field performance of the magnet by several percent.

The main conclusion is that with careful design, coupling via dipole ends can be kept within acceptable bounds with any of the magnet designs under consideration.

A6.1.1.3.3 Stray fields from spool piece correction coils

In contrast to the main dipoles, which are assumed to be always at the same excitation for E > 5 TeV, the trim coils in the spool pieces must be able to operate in all possible combinations with acceptably small coupling. The scale of the stray fields from spool pieces is set by the required strength of the trim dipole and the beam separation. The dipole strength is determined by the quadrupole alignment error and by the distance between quadrupoles. In the Reference Design Study, the dipole trim for the Ref. Design A magnet was required to have a strength of 5 T-m, with normal operation not expected to exceed 4 T-m. The requirement for superferric magnets is not expected to be greatly different. For purposes of this discussion, we take 5 T-m as the required strength in all designs. For reference purposes, we list beam separations and orientations in Table A6.1-1.

Table A6.1-1

Distance between beams.

Magnet Type	Beam Separation (cm)	Beam Orientation
A'	15.2	side-by-side
B	large	optional
C	12.4	over-under
D (1-in-1)	60-80	optional

For Ref. Design A magnets, it is possible to design trim coils which are assembled in a separate iron yoke for each ring (an example of which is sketched in the Reference Design Study) or in a two-in-one iron yoke. A calculation by Caspi indicates that small coupling can be obtained in a two-in-one yoke with fields at least up to 1.5 T.

For Ref. Design C magnets, the present plan is to use a short section of the standard dipole laminations, wound with many turns of a low current conductor to obtain the needed correction. As discussed in the next section, detailed calculations will be required to determine the maximum excitation which can be used without coupling into the other bore.

For Type D, it is possible to use the RDS Type A designs. Alternatively, a trim dipole design with lower stray field can be developed by placing the dipole winding near the beam tube. In either case, negligible coupling is expected.

For this report, it was assumed that it is possible to build uncoupled trim coils for any of the magnet designs by lengthening the trims until stray fields become acceptably low. The only difference then is the added cryogenic length required for a design with small beam separation or large integral strength. The added cryogenic length is estimated to be about 1%. It should be noted that detailed calculations will be necessary for any design because the directions of dipole fields in adjacent trims are orthogonal. Task force members expressed a strong sentiment against solving trim coil coupling problems by "appropriate" software algorithms, particularly in view of the hysteresis effects associated with superconductors.

A6.1.1.4 Magnetic coupling via permeability variations

This very non-linear form of coupling peaks as the iron in the magnet is saturating. The effect is proportional to the derivative of the permeability with field level (dμ/dB). Stray field from one magnet becomes concentrated in the iron yoke of another magnet. The beam in the second magnet never sees this stray field directly due to the shielding, but if dμ/dB is large, this stray flux can change the permeability and hence the reluctance of the magnetic circuit, thus acting directly on the primary flux of the second magnet. This could be called the "magnetic amplifier effect." It has been experienced in the CERN ISR, and is described in Appendix A6.3.

Calculation demonstrates that this is not a problem for the superferric magnet. With one bore "off" and the other at 3T, the field through the low field bore is a few tenths of a gauss. (Calculations for the more difficult case of 1T and 3T have not been done.)

A6.1.1.5 Beam-beam interactions

The beams are separated vertically or horizontally (depending upon bore orientation) to avoid the beam-beam interaction during filling and acceleration. The separation must be done carefully because partially colliding beams will be worse than head-on colliding or well-separated beams.

With equal RF frequencies in the two rings, one might imagine changing the RF phase to avoid collisions. However, the SSC bunch spacing appears to be too small to do this.

With asymmetric energies there is a stronger, resonant beam-beam interaction called overlap knock-out resonance(1,2) to be considered. There is some doubt that vertical separation will be sufficient to completely avoid this problem. However, an alternative solution may exist. Since the revolution frequency is only a slowly varying function of energy in the TeV range, one could lock the RF frequencies (and so completely avoid overlap knock-out) and accelerate one beam by at least a few TeV with respect to the other by allowing the accelerated beam to move to an off-axis orbit.

It is concluded that the beam-beam interaction will always be a factor requiring careful and complex operational procedures and possibly will require some additional hardware in the RF system. However, no differences due to magnet style were found.

A6.1.1.6 Other sources of interaction

The most important factor here is coupling through the cryogenic system. The cryogenic group felt it likely that a quench in one ring of a two-in-one magnet, such as in Ref. Designs A or C, would result in a quench in the other ring. This is likely to be a factor only at injection (see below), since both

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1. S. Myers, "Overlap knock-out with colliding bunched beams in the CERN ISR," CERN-ISR-RF/79-5 and 1979 Particle Accelerator Conference, San Francisco.

2. S. Myers, "Overlap knock-out resonances in the SSC," SSC-14 (1985 March), and A. Chou and C. Leemann, "More on the Overlap Knockout Resonances at the SSC," SSC-16 (1985 April). (These reports appear as Appendices 5.2 and 5.3 of this report.)

beams will have to be restored anyway if quenches occur at higher energies. The refrigeration load during recovery is higher in the two-in-one or dual case.

Other possible sources of coupling include the normally weaker interference between the rings arising from such elements as the control computer, which may be overloaded with requests from one of the rings, or perturbations transmitted via the main power supply when the power in one ring trips off.

A6.1.2 Effects of magnet style on ease of SSC beam manipulations

A6.1.2.1 Effect on overall collider activity

A6.1.2.1.1 Model for distribution of time

About a week is required to thermally cycle a portion of the SSC ring for magnet replacement or a similar repair (see Appendixes 4.4 and 6.8). It is essential, then, that the magnets be designed so that failures are infrequent. On the basis of Tevatron experience, we have assumed that the distribution of "events" which require a thermal cycle and replacement of one or more magnets is 5 in the first year of SSC operation (commissioning), 3 in the second year, and 2 per year thereafter. Two "events" then take 350 hours.

Although magnet replacement may be the most conspicuous source of machine downtime, it is not expected to dominate, based on the experience with existing accelerators. Rather, it is expected that most downtime will be due to the short-term failures which are spread over many systems. This has been the experience at the CERN SppS collider and at PEP. (A summary of the SppS collider performance is attached, Appendix 6.12; E. Patterson summarized the PEP experience in a talk at the Workshop.) Taking a rough average over the ISR lifetime (Appendix 6.4), it was assumed that the SSC would be scheduled to run 80% of the year (7000 hours). Of this, 50% of the time would be devoted to physics running, 25% to accelerator studies, with 25% downtime (1750 hours). With 350 hours (25% of the total failure time) lost to magnet replacement, one might expect the cause of half of the remaining downtime to be injection system problems because of its large number of systems. Cryogenic downtime was guessed to total 250 hours. Time lost to problems with controls, RF, and miscellaneous problems with the 20 TeV rings was estimated at 450 hours. In this model, replacement of a magnet reduces the number of hours of physics by about 5%. This model for the distribution of SSC time is compared with operations at the Tevatron, the SppS collider, the ISR, and PEP in Table A6.1-2. It can be seen that there is general agreement between the SSC model and previous experience except for the assumption that running would be scheduled 80% of the time, which was quite optimistic. It was felt that the SSC would be cold except for repair and that the additional power for operations would be small enough in comparison to the cryogenic load to permit this level of running.

A6.1.2.1.2 Commissioning

In the discussions during the Workshop, it was generally assumed that civil construction of the ring would proceed in several places at once and that magnet installation would follow soon thereafter. If this is the case, it would not be possible to complete one ring sufficiently ahead of the others to give any advantage to a two-ring design in terms of early commissioning. However, in the event of a magnet production interruption late in the production cycle, it would be an advantage if commissioning could begin in a single ring.

Table A6.1-2

Distribution of unscheduled downtime (=100%).

	SSC est.	Tevatron	PEP	ISR	S$\bar{p}$pS
Injector	40% (700)*	38% (894)	44% (546)†	41% (259)	"small"‡
Collider Ring	60% (1050)	62% (1487) ? → (1676)	56% (682)	59% (380)	

*Numbers in parentheses are estimated downtimes in h/yr.

†These numbers are for the 1983-84 cycle, when a great deal of SLC related work on the linac occurred. Injector downtime is normally about 1/3 of the PEP ring downtime.

‡See Appendix 6.12; Evans and Hatton do not discuss injector downtime.

Even if the magnet installation is completed on schedule, there is a clear advantage in having the two rings cryogenically and magnetically decoupled. The lesser of these two evils would be to have cryogenic coupling; magnetic coupling would be inconvenient to disastrous according to the level and the situation. The commissioning work on the two rings would not be in exact synchronism and if, for example, the closed orbit would be perturbed when the correctors in the other ring were cycled to test a control program, it would be a frustrating job to establish the first turn orbit.

A6.1.2.1.3 Accelerator studies

In the model of SSC time distribution presented above, about 1750 hours per year would be devoted to accelerator studies. The magnet style with the least amount of coupling will be able to make the most effective use of the time because it will be possible to run independent experiments in the two rings. In order to evaluate this advantage, we obtained data on accelerator studies time at the ISR, which are presented in Table A6.1-3. Ten consecutive schedules in 1973 and 1977, with about 300 hours of studies in each set of schedules, were reviewed. In each year, independent studies were carried on simultaneously about 45% of the time. For strongly-coupled magnets such as Design A, an additional 800 hours per

Table A6.1-3

Two data samples of accelerator R&D in the CERN ISR.

Category Group	A Independent experiment in each ring	B Experiment needing joint use of rings	C Exclusion or priority over other ring	Total hours
1(10 consecutive schedules in 1973)	113.5	118.0	56.5	288.0
2(10 consecutive schedules in 1977)	172.5	94.5	58.0	325.0

year would be required to accomplish the same amount of accelerator studies. This is about 1/4 of the scheduled physics hours. More likely, fewer accelerator studies would be done, but this also would reduce the integrated luminosity because improvements to the luminosity would come more slowly. The cumulative effect of accelerator studies on the luminosity can be seen in the ISR history, Fig. A6.4-3. The integrated luminosity in intersection region I5, which did not benefit from the low-beta insertions, increased more than a factor of 20 over 13 years.

We now look at the distribution of accelerator down-time to estimate the amount of accelerator study which can be carried on during repairs. Magnet styles which are cryogenically independent will allow studies during most (300 hours) of the 350 hours estimated for magnet replacement. There would be a similar gain during some fraction of the 250 hours estimated for cryogenic repairs, say 100 hours. During the remainder of the down-time, predominantly injector problems, there would be no difference in magnet styles. The total 400 hours of additional single-ring studies, taken to be equivalent to 200 hours of studies time with independent rings, is about 5% of the physics hours. This estimate is in good agreement with R. Orr's extrapolation from an analysis of Tevatron downtime, given in Appendix A6.9.

A6.1.2.1.4 Physics with equal beam energies

Since the various reference magnets have been designed with collider operation at equal energies as the primary goal, it is not surprising that there is no significant difference in how well each style performs. (The questions of required aperture and field quality are dealt with elsewhere.) Here we reiterate the conclusion of Section A6.1.3: The trim coils in the spool pieces must be totally decoupled. This is possible in any design, the penalty (if any) for small beam separation being additional cryogenic length.

A6.1.2.2 Effects of specific beam manipulations

A6.1.2.2.1 Injection

1. Relative beam orientation

Whether the relative beam orientation presents a problem with respect to injection depends on the placement of the high energy booster and the injection lines. If it is more convenient to inject in the horizontal plane, as in the reference design, then an over/under configuration is preferable. If, on the other hand, injection in the vertical plane is used, a side-by-side configuration is better.

2. Beam separation

As in the abort system (discussed later), there are a number of large conventional magnets associated with the injection lines and straight sections. These will require a certain amount of space between the beam lines. A one-in-one design, with its flexibility and intrinsically larger beam separation, is preferred over a two-in-one design, with its constrained, closely spaced beams.

3. Beam loss

In a superconducting accelerator, problems arising from beam loss causing magnet quenches can be regarded as inevitable. In assessing the effect of magnet style on this aspect of machine performance the two basic questions which must be addressed are:

-- is any magnet type likely to behave differently under situations involving beam loss?

-- when an element does quench do any of the different designs have any significantly different responses in terms of operational consequences?

Based on experience with existing machines, it is possible to define areas in the lattice as high risk for beam loss (beam transfer areas, critical apertures, IR's) and other regions (standard arcs) as relatively benign. The overall characteristics of the lattices are similar enough that the various dynamic mechanisms which would produce beam loss will be essentially the same for all cases, but the layout of the lattice in these high risk areas will vary with magnet style, and some layouts will be easier to build than others. For example, the injection straight section is likely to have large losses. This is due less to the process of injecting the beam than to the beam optics, and the necessity of putting steering bumps in the circulating beam to avoid septa and to close the orbit. Because of the possibility of losses, it would be best if there were some conventional bending in the straight sections, and if magnets near the straight section were of the conventional rather than superconducting type. As mentioned later (in the section on abort), these aims are more easily accomplished in a one-in-one design.

Differences in magnet aperture may be relevant in the vicinity of the IR's, where the high luminosities produce a significant DC heat load on the elements close to the interaction point. These effects however disappear rapidly as the distance from the IR increases, and should not pose any problems in the arcs. The effect of different apertures in the arcs on the beam loss mechanisms will be small. Simulation work on the Tevatron indicates that small changes in the aperture in regions other than the critical apertures have little effect on losses.

The one aspect of this problem where magnet style may have an effect is the ability of the magnets to tolerate beam loss. Magnets quench because of temperature increases in the superconductor which in turn is related to the density of energy deposition in the coils. Differences in magnet geometry, number of turns, cooling channels, and operating temperature all strongly effect the ability of the magnet to tolerate heat loading. Computer simulation is the only reliable way to calculate these effects, but unless a particular magnet shows orders-of-magnitude difference in quench threshold levels the operational consequences will be small. An example of this is the loss associated with injection due to the misfiring of one of the kicker modules. This will put a large betatron oscillation in the beam.

This can cause problems not only at the injection area, but over a significant part of the machine. It is typical at the Tevatron to quench magnets at the injection area, and two or three other areas separated by integral numbers of betatron wavelengths. In this case, it is unlikely that having conventional bends near the straight sections will prevent extensive beam loss and the resulting quenches. The amount of beam lost at the various places where the beam scrapes in the case of a kicker misfire is quite large--many times the amount needed to start a quench even in the most stable superconductor.

For all the magnet designs in which both beams are in the same cryostat, quenching is almost certain to automatically occur in both beams irrespective of which one initiated the quench. The so-called one-in-one designs can, in theory, quench in one ring and leave beam circulating in the other one. (This scenario presupposes that the abort system has the capability to differentiate between losses in the separate rings.) This then poses the question of whether it is operationally useful to preserve a single beam circulating at high field when the other one has gone away. If the beams are coupled in energy for any reason then little is gained in attempting to maintain the second one. Estimates of setting-up time for physics lie in the 2-4 hour range, of which only 15 minutes is used to fill the ring--a small saving at best. (See Appendix 6.7.) Recycling the persistent currents would involve decelerating the still-circulating beam below injection energy where it is unlikely to survive in any case.

If an IR design can be made where the beams are not coupled in energy, then one can imagine leaving the circulating beam at high energy while the second one is refilled. Here the time saved in setting up might be greater than in the energy-coupled case (~1 hour) but again when this is traded off against the fact that the luminosity for the run would be lower (one beam is old) and setting up procedures would be different, then one is led to the conclusion that we would probably choose to dump the second beam and just start over.

In the case of quenches occurring during the injection procedure, which are likely to occur during the commissioning phase of the machine, the same conclusion does not hold. In this case, being able to save one beam may significantly decrease the efficiency of the machine, and there would be a clear advantage to the cryogenically decoupled magnet types. However, injection quenches are not a significant source of downtime at the Tevatron.

In conclusion, we can say that provided the different magnets designs do not show radically different capabilities in their tolerance to beam losses, then the operational consequences of the various schemes and the associated lattices with respect to beam loss and magnet quenches are not significantly different for two-in-one or dual magnets. But with decoupled IR's, the one-in-one magnets have an advantage because of their cryogenic independence.

4. Variations with ring size

It will take twice as long to fill each ring of a 3T design as it will to fill each 6T design. If the high energy booster cycles once per minute, it takes 15 minutes per ring to fill the 6T machine, and 30 minutes per ring for the 3T. It is expected that the total difference of 30 minutes will be short compared to the total amount of time that it will take to fill and commence a physics run. This time is expected to be between 2.0 hours and 4.0 hours for the 6T design (Appendix 6.7).

5. Injection field quality

A degradation of the field quality of the magnets at injection energy can be due to two causes: (1) Persistent currents in the superconductor, and (2) variations in the permeability of the steel used in the return yoke. These problems will be discussed in detail in the Aperture Taskforce Report. Here, we will only summarize. The persistent current problem is more severe in the higher field, cosθ type of magnet, because of the large amount of superconductor close to the beam. There are some potential fixes to the problem, ranging from the simple (but costly) solution of enlarging the coil inner diameter or increasing injection energy, to independently powered sextupole and decapole correction coils in each dipole. The latter solution would involve a large number, anywhere from 100 to 10000 small power supplies, with associated cryogenic feedthroughs, cryogenic temperature measuring devices, and controls. That solution would clearly complicate the operation of the machine. There are other more passive solutions possible, each requiring some R&D effort, and resulting in increased cost.

The superferric type of magnet has a problem with the random variation of the iron permeability. It is generally assumed (though not proven) that random fluxations in the permeability can be minimized by shuffling the steel and/or shuffling magnet positions in the ring.

It is quite possible that the persistent current problem intrinsic to the high-field $\cos\theta$ magnets will be more difficult or expensive to solve than the problem of permeability variations in steel used in the 3T magnets. In fact, it may be the most difficult R&D problem connected with the $\cos\theta$ magnets.

A6.1.2.2.2 Acceleration

In the Reference Designs Study, it was assumed that the acceleration of the beams to 20 TeV would be done in approximately 1000 seconds at a constant ramp rate. This required about 20 MV of RF voltage, and 2 MW of RF power. For the 3T rings, the voltage required for the same constant ramp rate would be 40 MV, and 4 MW of RF power. A slower initial ramp rate would decrease the power requirement without substantially increasing total ramping time. This and related problems are discussed in Section 5.1.3.

A6.1.2.2.3 Interaction region operation for colliding beams.

The interaction regions are expected to be rather similar to one another, more or less independent of the magnet type used in the arcs. The very high gradient quadrupoles of large aperture will require a $\cos 2\theta$ design, even in the case where a superferric design is used in the arcs. There are, nevertheless, a few significant differences.

1. Relative beam spacing

The two beam lines in the one-in-one case will be 60 cm to 80 cm apart. This will require a much more substantial bend to bring the beams into collision than in the case of two-in-one or dual magnets, with their closely spaced beams. In principle this will take more dipole or drift length. However, if the dispersion is to be exactly cancelled at the interaction point, that length may be needed in any case. Whether there is an actual penalty in length remains to be seen, after a detailed design of the IR's is complete.

A potentially more difficult problem has to do with the close spacing of the beams in the two-in-one and superferric designs. Most designs of the IR's will have not only strong quadrupoles common to the two beams, but will have equally strong quads that are separate, between the ends of the arcs, and the beam convergence dipoles. As mentioned above, these quads will probably be of a cos2θ design, since they are very strong, near 250 T/m. It is not clear that such quadrupoles can be built within the constraints of closely spaced beams. One solution, of course, would be to split the beams apart, insert the strong quads, and bring the beams back together. This, of course, introduces additional dispersion.

2. Beam orientation

The only relevant operational consideration evaluated by the Task Force was the replacement of one-in-one magnets. It was assumed that the there would be direct access to only one ring if the magnets were installed side-by-side. Replacement of magnets in the farther ring would require more fixturing and take longer than replacement of magnets in an over-under configuration.

It is possible that magnets in a side-by-side configuration are more sensitive to being quenched by beam losses in the adjacent ring than magnets in an over-under configuration. (This is an issue only for one-in-one magnets since the cryogenic coupling of two-in-one magnets means that both will quench when either initiates the quench. However, the issue cannot be further evaluated without detailed calculations, e.g. based upon experience with CBA modeling.

Except for such magnet replacement considerations, beam orientation is largely a design issue, not an operations issue. Over/under configurations introduce vertical dispersion at the IR's because of the vertical bend required to bring the beams together. It is thought such such dispersion can be corrected in straightforeward ways (e.g. by using "purposely imperfect" dispersion suppressors before the insertion regions) without adding significantly to the circumference of the machine. The side-by-side configuration requires such dispersion suppressors in any case.

One problem with the side-by-side configuration comes about because the beams must have equal path lengths to avoid having the gap(s) walk around the machine relative to the bunches. This puts restrictions on the utility insertions (and any other insertions). Whether this problem (the "Pac Man Effect") is real remains to be seen.

A6.1.2.2.4 Beam dumping

With 400 MJ of stored energy in each of the two 20 TeV SSC beams even in the 6T case, it is imperative that the abort system be fail-safe. It must be able to remove the beam from the machine cleanly even in a worst-case scenario. This is especially true in a superconducting accelerator, because superconducting magnets are particularly sensitive to beam losses. Losses as small as one part in 10^4 or less of the circulating beam could make superconducting magnets go normal (quench), requiring hours for recovery. For a detailed description of a possible abort scheme, the reader is referred to the RDS, sections 5.1.8 (pp 253 ff) and A.1.8 (pp A.199 ff).

1. Dependence on circumference

The most obvious difference in abort requirements is due to the different machine circumferences. The 6T machine has a circulation period of about 300 µs, and a total stored energy in each beam of about 400 MJ. The 3T machine has a circulation period of about

530 µs, and energy approaching 800 MJ per beam. These parameters raise at least three points of comparison:

1.1 Delay time to safe abort

In order to have a clean abort, the kickers must be energized at a time when a gap in the beam is present at the kicker location. If this is not done, the finite rise time of the kickers will cause beam to be sprayed around the machine, resulting in multiple quenches or even more severe damage. The gap (or gaps) in the beam are a few microseconds long, or of the order of a kilometer.

The signal used to abort the beam can be generated anywhere in the ring. It is then transported to the abort location, and put in coincidence with the passage of the beam gap.

The maximum time required to begin and complete the abort sequence is shown in Table A6.1-4, starting from the decision to abort the beam. The time taken to make that decision will depend on the cause of the abort, and might vary from a fraction of a microsecond to a few milliseconds.

It is unlikely that the factor of two will make a significant difference in the probability of damage to the machines. A typical problem might be that a correction dipole quenches, causing a missteering of the beam, resulting in high losses. Such events usually become critical in tens of milliseconds, large compared to the

Table A6.1-4

	6T	3T
Signal Transport	180 µs	290 µs
Gap coincidence	300 µs	530 µs
End of Abort	300 µs	530 µs
Total	780 µs	1350 µs

values in the table. This conclusion may change, depending on detailed design of the magnets and quench protection. Even with the much faster abort system on the Tevatron, beam loss quenches occur. Whatever is making the beam misbehave will have about twice as long to do its bad work in the 3T case, making the beam less clean for abort. However, it is probable that if 1400 μs presents a problem, then 800 μs does also.

2. Total on-time of abort kickers

The abort kickers are substantial devices, since they have to bend a 20 Tev beam by approximately 100 μrads, have a fast rise time, and stay on for a considerable time. In the 3T case they must stay on twice as long. This implies more energy storage and more energy dissipation in the kickers, with increased cost and design difficulty. The modification would cost about \$2M (1984 \$). A case might be made for two separate beam dumps in the 3T ring case. Duplication of the complete system would cost \$6M.

2.1 Total stored beam energy

The beam in the 6T design has a total stored energy of about 400MJ. In the 3T design, this number approaches 800 MJ. The major implications of the 3T design are: (a) the possibility of more serious damage caused by catastrophic loss of the beam, or abort system was malfunction, and (b) the abort dump withstanding twice as much energy, under the fault conditions assumed in the RDS. From the RDS, it appears that the graphite-pellet dump could withstand several gigajoules if all the abort systems work properly. In the event of failure of the external kickers, (used to spread the beam across the dump, thus keeping the energy density low) there is the possibility of damage to the dump, or to its beam entrance windows. In this failure mode, the beam hitting the dump will have $\sigma_V = 6$ mm and $\sigma_H = 14$ mm. In this case, the peak energy density would be about 0.5 GeV/cm^3/proton in graphite.(3) This leads to ~6 x 10^{13} GeV/cm^3

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3. CERN preprint DIR-TECH/84-01, "Large Hadron Collider in the LEP Tunnel," CERN Machine Group, May 1984.

in the 6T case (2.3 x 10^{14} protons), and ~1.0 x 10^{14} GeV/cm^3 in the 3T case. The result is barely tolerable in the 6T case. For the 3T case, the beam blow-up lenses will have to be stronger, or the dump put further away.

3. Dependence on beam separation distance

3.1 Beam loss

In the abort region of the SSC, the design must allow for significant beam loss. This is done in two ways: (1) The elements used in the abort system are conventional, that is, no superconducting elements are used. (2) The beam is bent going in and out of the abort region, with conventional magnets, so that secondaries produced by scraping beam are swept away before they can cause problems in the superconducting elements. In the Reference Designs, the beams are split apart by a series of conventional dipoles that straddle both beams. This not only sweeps secondaries, but spreads the beams apart, allowing enough room for the large conventional magnets. Nevertheless, there was not enough beam separation to use conventional quadrupoles to match to the abort straight section. This is a potentially serious problem. Any design with very closely spaced beams will have this problem, and will require either much more bend than shown in the Reference Design, or a much longer straight section, or both. A one-in-one design, with beams separated in the arcs by 60 to 80 cm has enough room to use the conventional devices in the arcs near the abort region. This is a significant advantage in design flexibility.

4. Dependence on beam orientation

4.1 Side-by-side

When the beams are side-by-side, particularly in the two-in-one case, and the abort straight sections for both beams are installed in the same region, one beam must be bent to the inside of the ring, the other to the outside. This results in one of the extracted beam lines obstructing the vehicular aisle of the tunnel. This problem was solved in the Reference Design by bending the beam down into the floor after it emerged from the accelerator. This requires a considerable amount of conventional bend magnet, operating power, and cooling water. An over/under design does not suffer this problem, since the beams can be bent horizontally in the same direction. However, if the beams are very close together, some vertical bend will be required to separate the beams in order to be able to insert the large conventional magnets required for the abort. Again, one-in-one is more flexible, and a over/under design is easier to implement.

A6.1.3 Possible additional physics tasks

The focus here was on developing a fairly complete list of additional tasks. Only the most obvious features of each task were considered in making up the rating (Table A6.1-5). The tasks themselves were not rated in importance.

Table A6.1-5

Magnet ratings for additional accelerator tasks.
(Scale: each magnet scores 10 points for proton-proton collisions at equal energies)

Task	Magnet Type			
	A	B	C	D
Proton-antiproton - one ring	4	10	6	9
Proton-antiproton - two rings	0?	--	--	--
Proton-polarized protons (gas jet)	10	10	10	10
Polarized proton-polarized proton	5?	10	5?	10
Electron-proton	10	10	10	10
Fixed target program	1	1	5	1
Proton-proton (asymmetric energies)	0	--	--	--
Heavy ions	?	?	?	?

In the single ring proton-antiproton (p-pbar) collider case, magnets were rated on the basis of physical aperture, except that Design A was also downgraded because the strong magnetic coupling required that both rings be powered even though only one is used. Design A magnets preclude the use of both rings for proton-antiproton collisions because the dipole fields in the two rings must be opposite one another. No rating is given for the other magnet styles for two-ring p-pbar operation because no assessment could be made of the possibility of designing insertion regions for this type of operation.

A gas jet target of polarized protons could be used in a single ring to study interactions in a fixed target mode. It was estimated that the density of the gas in the jet would have little effect on the lifetime of the bunches, so that the gas jet could be run in one interaction region while collider physics continued in the others. A study by Courant(4) indicates that polarized protons can be accelerated in the SSC. Polarization is preserved by the use of magnets which control the spin precession. It was felt that the small beam separation of Designs A and C will make the construction of the necessary polarization-rotation magnets ("Siberian snakes") more difficult than for the other two designs.

For electron-proton operation, it was assumed that the electrons would be accelerated in a ring of conventional magnets. The same single-IR operation as for the polarized gas jet was assumed.

For a fixed target program (test beams or physics) with the 20 TeV ring, rapid cycling of the ring is desired. The heat load due to AC losses in the superconductor and hysteric losses in the iron becomes the limiting factor in the ramp rate. No magnet is well suited to rapid cycling, but it was felt that the superferric design would be better than the others. However, no estimates of either source of heating were made.

Proton-proton physics at asymmetric energies is difficult for any magnet style because in the present design of the insertion, magnets are common to

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4. E.D. Courant, "Possibilities of Polarized Protons in SPPS and Other High Energy Hadron Colliders," Proc. 6th Intn'l. Conf. on High Energy Spin Physics, 1984, to be published and BNL #36181.

both rings and a solution with separate elements will be very demanding technically. Design A magnets cannot be run asymmetrically at high energy.

It may well be that the SSC aperture is too small for the emittance of beams of heavy ions such as gold. If the emittance problem can be solved, it is desirable to be able to have different ions in the two rings. This option was felt to be necessary for the BNL heavy ion collider design (RHIC). Different species require that the two rings be run asymmetrically, which is impossible for Design A magnets. In a heavy ion collider, intra-beam scattering may be the most important factor in the luminosity lifetime, although beam-beam electromagnetic effects and synchrotron radiation need to be evaluated also. At this time the answer is unclear.

When the numbers for each magnet style are added, approximately equal score to Designs B, C, and D result. Design A scores somewhat lower overall.

A6.1.4 Flexibility, simplicity, reliability, and impact on integrated luminosity

In this section we list several criteria for magnet evaluation which are clearly important but also difficult to quantify. The criteria are flexibility, simplicity, reliability, and integrated luminosity.

The easiest topic to discuss is flexibility. The magnet types can be evaluated in terms of flexibility of response to unexpected problems in the SSC, in terms of their upgrade potential for higher energy pp collisions, and in terms of their ability to perform other types of physics. Unexpected problems are very likely inevitable. One example might be problems with magnet production in the second half of the production cycle. In this instance, it would be possible to complete one ring of Design B or D magnets and begin accelerator studies without having to wait for production to resume. Another type of unexpected problem could be large beam losses at injection. In this case, the larger copper-to-superconductor ratio of Design C would be an advantage. For an upgrade to higher-energy collisions, with the SSC the presumed injector, the longer tunnel of Design C has the advantage. Adaptability to other types of colliding beam physics or to fixed target physics was discussed in detail in Section A6.1.3, where it was concluded that Design A is at a disadvantage relative to the other designs.

For the present, we treat simplicity, reliability, and integrated luminosity together. We begin by referring to E. Patterson's analysis of PEP downtime which was presented at the SSC Commissioning and Operations Workshop and which is summarized in Table A6.1-2. Patterson summarized his study by remarking that downtime will be dominated by short term faults which cause beam loss. In particular, complex systems which require protection interlocks will require careful fault analysis.

There is, of course, reliability information on magnets which are similar to the proposed SSC designs. The performance and problems of nearly 800 Tevatron cosθ dipoles, over 200 quadrupoles, and over 200 spool piece trim coils are generally understood. The lifecycle testing of the short and long magnet strings should lead to a reliable design for the SSC. The two window-frame magnets (2m, 3.5T) built by G. Danby et al. and used for a decade in the AGS extracted proton line are similar to Design C magnets, and are evidence against some previously unimagined degradation which might take place on a long term time scale.

One approach to reliability is to count the number of elements, assuming that reliability decreases as the number increases. However, it is not clear what to count (e.g., the number of cryostats or the total number of connections made to and inside each cryostat) or whether there should be a weighting by complexity (e.g., the method of handling thermal contraction). In addition, reliability considerations must also focus on the lengths of the magnets, independent of magnet style. There is no experience with the mass production of 150 m long objects which must undergo 18 inches of thermal contraction during a cooldown. With proper R&D, the problems due to thermal contraction should not affect the magnet lifetime. However, these problems will affect the uncertainty of the magnet R&D program in that R&D for a magnet closer to Tevatron/CBA length is more likely to follow a predictable timetable and cost schedule than R&D for a much longer device.

In summary, previous experience led the taskforce to conclude that reliable magnets could be designed. However, in the absence of a detailed design and a failure mode analysis, it was not possible to evalute the relative reliability of different magnet styles.

A6.1.5 Summary table and conclusions

The summary table (Table A6.1-6) was developed by the Task Force as a whole after extensive discussion of the issues. Here we briefly review the issues, referring to the main text for detailed discussion.

Dipole decoupling for low energy would allow the beam in one ring to be accelerated to a significantly higher energy immediately after injection, rather than waiting 15 min or 30 min for the other ring to be filled. This capability would be an advantage if the beam lifetime at injection were somewhat shorter than anticipated. Coupling of the various designs is discussed in Sections A61.3.1 and A6.1.3.2, where it was concluded that all magnet designs (even Design A) will be uncoupled below 5 TeV. Above 5 TeV, for equal energies, coupling between the straight sections of the magnets appears to be satisfactorily small. Coupling limits for the end fields have not been specified. If they are tight, they could be expensive to achieve.

As with the main dipoles, there should be no significant ring-to-ring coupling of the trim coils. Unlike the dipole case, however, all possible combinations of excitation for the trim coils must be explored in order to assure the necessary independence. It was concluded that this could be achieved for any magnet design, with small differences in cryogenic length between the designs (Sections A6.1.3.3 and A6.1.3.4).

The capability of single ring operation during repairs will increase the time available for accelerator studies and for certain types of physics, such as gas jet (Section A6.2.1.3). It would also be an advantage if magnet construction is delayed (Section A6.2.1.2).

At present, only in the Design A magnet are the rings side-by-side. Designs B, C, and D are proposed as over-under configurations. The Design group found no significant differences between the two configurations for the operations listed in the table. Because of the difficulty of estimating the effects of beam losses on adjacent rings, it is unclear whether a one-in-one side-by-side configuration would experience quenches in both rings more often than an over/under arrangement. A compact IR design for an over-under configuration does not yet exist, but it has been declared possible. (The ease of installation and removal enters only for a possible "dual" design, where the

Table A6.1-5

Magnet style evaluation for SSC beam gymnastics and other considerations.

(For importance, a score of 10 means essential; 5 means advantageous. For capability, 10 means integral to design and therefore easy, 5 means possible but extra work required, 0 means impossible.)

ISSUE	Importance	CAPABILITY Design A	 Design B	 Design C	 Design D
1. Dipoles decoupled for E<5 TeV	5	10	10	10	10
2. Trims decoupled at all excitations	10	10	10	10	10
3. Single ring operation (physics or accelerator studies)	5				
a. one ring cold		0	10	0	10
b. both rings cold, but only one ring up		0	10	10	10
4. Ring orientation implications for	5				
a. beam abort					
b. injection					
c. beam loss		?	?	?	?
d. IR design-dispersion corrections					
e. IR design-beam spacing					
5. Ring circumference implications for	10				
a. beam abort		10	10	6	10
b. instabilities					
c. filling time		10	10	10	10
6. Correction elements	5				
a. operational complications		5	5	10	5
b. total number of supplies		8	8	8	8
7. Flexibility for	10				
a. additional physics programs (Table A6.1.3.1)	(5?)	6	10	8	10
b. energy upgrade	(5?)	5	5	10	5
c. unexpected problems	(10?)	5	10	7	10
8. Simplicity, Reliability, Integral Luminosity	10	?	?	?	?
9. Recovery time for injection quenches	5	8	10	8	10
10. Commissioning	10	2	10	6	10

magnets would be side-by-side in a single cryostat and more difficult to remove in a small tunnel.)

Nor does the circumference of the tunnel (about 100 km for Designs A, B, and D; 180 km for Design C) have an important effect on beam gymnastics. The Design group studied beam instabilities at injection and storage and found no differences. Construction of the beam abort system will be more difficult for Design C because the system would have to deal with twice the number of protons (Section A6.1.2.2.4). For the same reason it will take twice as long to fill the larger ring, but this is small compared to the 12 hr estimate for the overall time between physics runs (Appendix 6.7).

Each magnet style requires correction elements specific to that style. The cos (θ) designs (A, B, D) will probably require "local" correction of the sextupole fields produced by magnetization effects in the superconductor (Section A6.2.2.1). This effect is largest at injection. In the superferric design (C), the second and third currents generate dipole field and are also needed to keep the sextupole and decapole harmonics small over the full energy range. The number of power supplies required for each of the magnet types has been tallied in the report of the Systems Group.

Three aspects of "flexibility" were considered. The most important (essential) issue of this has to do with the difficulty of implementing changes made necessary by unexpected problems. Designs B and D, which have the least coupling and greatest distance between rings, were seen as the most flexible in this respect. The ability to adapt to added physics programs (Section A6.3) is summarized under flexibility. An upgrade in energy was presumed to take place by installing higher field magnets in the existing SSC tunnel. The greatest gain will be achieved with the longest tunnel, Design C.

In the absence of a detailed failure mode analysis, no rating for the general considerations of simplicity, reliability, or integral luminosity has been given. This entry remains in the table as an indication of its importance.

Based on experience with the Tevatron, one might expect most SSC magnet quenches to occur at injection, where they will not be an important contributor to SSC downtime. Cryogenically coupled magnets take longer to recover from a quench. Also, for about half the quenches, a full ring's worth of beam will be lost. On the other hand, Design C magnets, with a higher copper-to-superconductor ratio, will be more stable than the other designs.

During commissioning it will be particularly advantageous to have uncoupled rings (Section A6.1.2.1.2). Magnetic coupling is much worse than cryogenic coupling for independent work on the two rings.

Appendix 6.2

FINAL EXPERIENCE WITH STRAY-FIELD COUPLING FROM COIL ENDS

The main accelerator tunnel at Fermilab houses both the Main Ring and the Tevatron with the two machines separated vertically by 65 cm. The onset of the colliding beam era requires, for various reasons, that the two machines operate in an independent fashion. More specifically, the Main Ring (MR) must be able to receive and accelerate beam while the Tevatron executes the fixed target program. The Tevatron fixed target cycle takes ~60 seconds during which time the beam is injected at 150 GeV, accelerated for ~16 seconds, extracted for 20 seconds and then ramped down at approximately the same rate. During this time many Main Ring cycles are performed particularly for the purpose of studies and improvement. It became immediately obvious that the Main Ring performance was strongly affected by the Tevatron cycle, and in particular the injection characteristics at 8 GeV. The basic problem was identified as being due to stray fields from the Tevatron although line loading from the power supplies is also present. An analysis of the MR injection closed orbit showed that the predominant concern was in the areas where unshielded beam pipe was exposed to fields, i.e. not in the arcs. This was subsequently confirmed by power-on tunnel measurements. The Tevatron stray fields which were important came from two main sources: the beam transfer magnets located in various straight sections and fields arising from the ends of the Tevatron dipoles in those few areas of the lattice where the MR dipoles did not provide shielding. Tunnel measurements of the stray fields from a dipole end at a vertical offset of 55 cm give

$$\int B\cdot dL_V = 2 \text{ G-m (approx. 2G for 1 m)}$$
$$\int B\cdot dL_H = 0.2 \text{ G-m} .$$

These fields produced closed orbit distortion, tune shifts and presumably higher order effects.

To date the partial solutions to these problems have involved magnetic shielding, which has given a factor of 3-4 improvement, and dynamic corrections to both orbits and tune (and injection line) which vary element settings as a function of Tevatron current.

Appendix 6.3

CERN ISR EXPERIENCE WITH COUPLING VIA PERMEABILITY VARIATIONS

This effect was first seen in the ISR in 1982. Although it was always present, it was only the special combination of the extremely sensitive optics of the superconducting low-β insertion with phase displacement acceleration to the maximum ISR energy that caused the effect to become serious.

In Fig. A6.3-1 there are two adjacent magnet blocks. The stray field from the ring 1 block is concentrated in the back yoke of the ring 2 block. The ring 1 beam does not see the stray field directly because of the shielding from the yoke, but instead sees the concentration of the stray field in the yoke changes the permeability slightly which then alters the reluctance of the magnetic circuit, thus changing the primary flux in the magnet block. For 11 years, this was an insignificant effect in the ISR but the superconducting low-β insertion opened a wide stopband around the $Q = 9$ integer resonance and parameters became so sensitive that the closed orbit could move 10 mm due to this effect, even in a machine as weakly coupled as the ISR. The effect is concentrated in the 4 or 5 blocks adjacent to each intersection where the rings are close together.

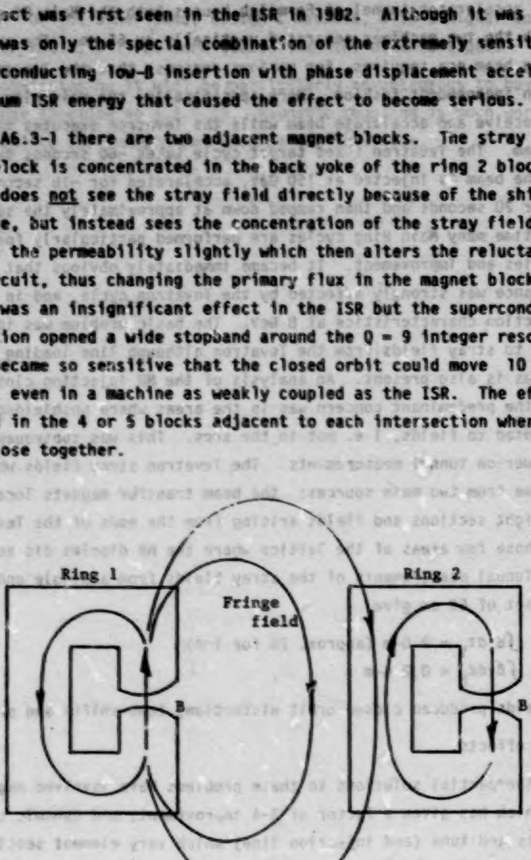

Fig. A6.3-1. Fringe-field coupling in the CERN ISR.

Appendix 6.4

OPERATIONAL HISTORY OF THE CERN ISR

Figures A6.4-1 through A6.4-3 summarize the 13 year operating life of the ISR with colliding beams.

Figure A6.4-1 shows the scheduled hours, achieved hours, achieved physics hours and the downtime due to the ISR rather than the preceding machines in the chain, i.e., the linac, booster and PS. There is a basic trend to increase the scheduled hours, with a dip around 1979-80, and the maximum of 5767h was achieved in the final year 1984. However, the ratios of achieved hours, achieved physics hours and ISR Fault time to scheduled hour remain essentially stable throughout the 13 years.

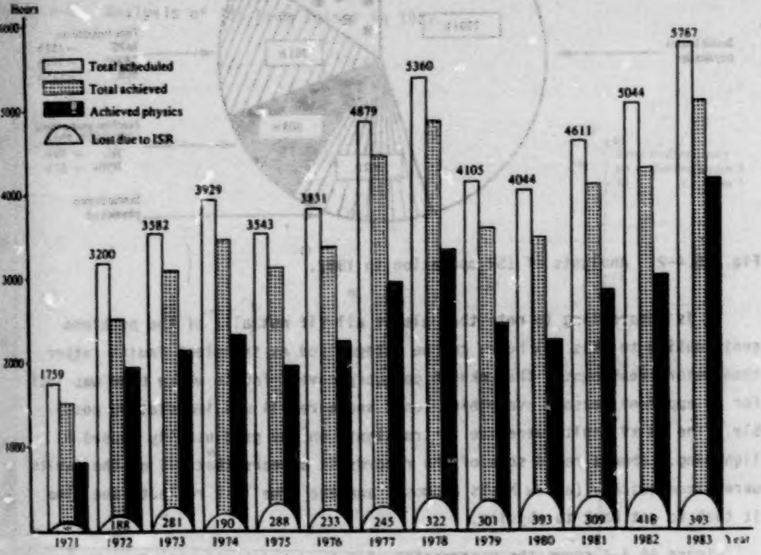

Fig. A6.4-1. History of total scheduled hours, total achieved hours, and achieved physics hours at the CERN ISR.

A6.4-2

As regards the time lost from physics in the ISR, Fig. A6.4-2 shows a breakdown for a typical year (1982). There is no detailed information readily available but an analysis of the records has revealed some additional information on the 761 hours of time lost (152 hours--injector, 191 hours--18 kV supply, 418 hours--ISR). Listed below in Fig. A6.4-3 are the faults which caused beam loss and their frequencies.

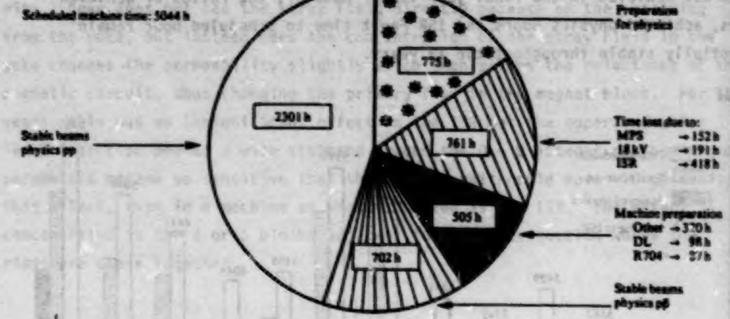

Fig. A6.4-2. Analysis of ISR operation in 1982.

It is interesting to note that almost all (if not all) of the problems contributing to this 761 hours can be categorised as transient faults rather than major breakdowns. The unknown category covers faults where beam was lost for no apparent reason, everything reset and a refill was immediately possible. The 18 kV faults were due to transients on the grid usually caused by lightning. From a rapid scan of the records it appears that all of the faults were fixed quickly (a few hours at most) and the time lost reflects the time it took to get back to physics.

Figure A6.4-4 shows the progression of integrated luminosity for physics measured in the reference intersection I5 (no low-β insertion) and the achieved hours for physics. The integrated luminosity increases more than 20-fold over the 13 years and this is in fact an underestimate, since it is not weighted for the introduction of the low-β schemes in intersections 1 and 8.

CAUSE	NUMBER
Unknown	8
18 kV	6
ISR Magnets and supplies	3
Experimental equipment	3
Water cooling	2
Vacuum	2
Faults in transformers at CERN but not ISR	2
Feedback	2
Operator (Q-shift)	1

Fig. A6.4-3. Analysis of ISR beam losses in 1982.

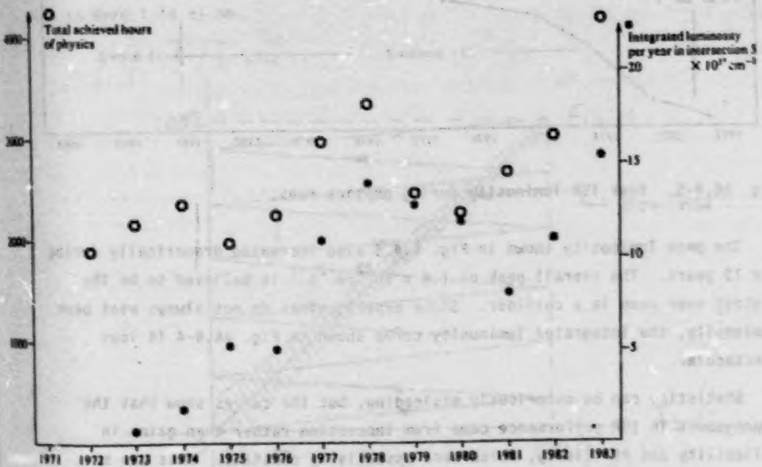

Fig. A6.4-4. CERN ISR operations for physics achieved at the end of each year.

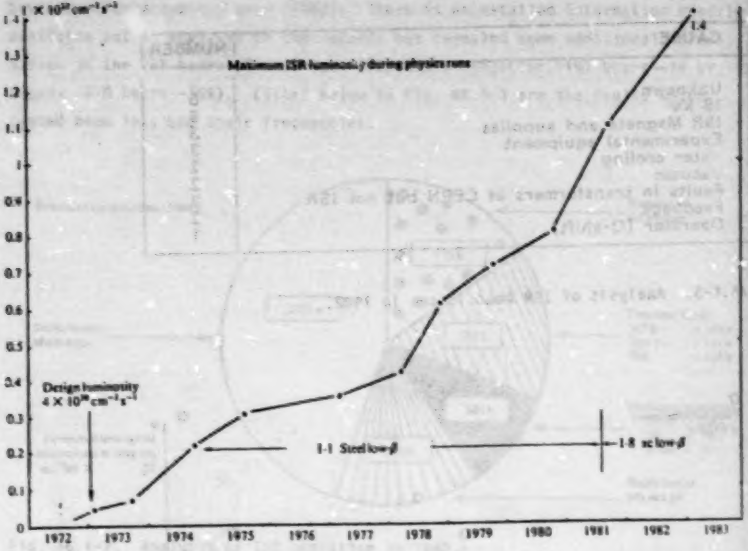

Fig. A6.4-5. Peak ISR luminosity during physics runs.

The peak luminosity shown in Fig. 6.4.5 also increased dramatically during the 13 years. The overall peak of 1.4 x $10^{32}\text{cm}^{-2}\text{s}^{-1}$ is believed to be the highest ever seen in a collider. Since experimenters do not always want peak luminosity, the integrated luminosity curve shown in Fig. A6.4-4 is less spectacular.

Statistics can be notoriously misleading, but the curves show that the improvement in ISR performance came from innovation rather than gains in reliability and efficiency, which were essentially constant. This can be interpreted as a justification for the accelerator research and development time, which when viewed on the short-term day-to-day basis always has a low priority.

Appendix 6.5

MAGNETIC COUPLING FOR THE FULL RANGE OF EXCITATIONS

Although the discussion of coupling in the main text of this report is limited to SSC energies near injection, it is useful to outline the effort required to evaluate coupling over the full range of excitation. As an illustration, a typical measuring program might vary the currents in the two bores as shown in Fig. 6.5-1. Current I_2 would be cycled while measuring the field in Bore 1, as I_1 is slowly ramped. (The field in Bore 2 is not measured because it is the perturbing influence and is not following a standard cycle.)

The result of such a measurment would be a set of curves, illustrated schematically in Fig. 6.5-2. Each shows the excursion of B_1 from its nominal value B_{10}, as B_2 is ramped. For example, for B_{10} = 40% of full field, but deviates elsewhere. There is some envelope of permitted values, indicated by the cross-hatched region in both figures, where e.g. the maximum orbit distortion in Bore 1 is ±1 mm.

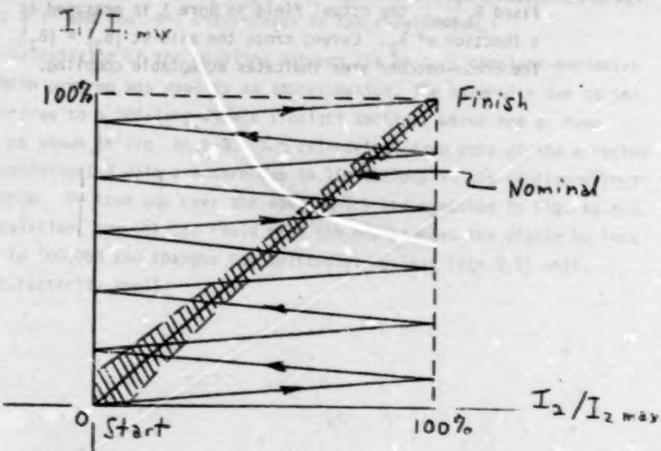

Fig. 6.5-1. Current scan program for measuring excitation in Bore 1. Cross-hatched region is a typical "allowed" region for acceptable orbit distortion.

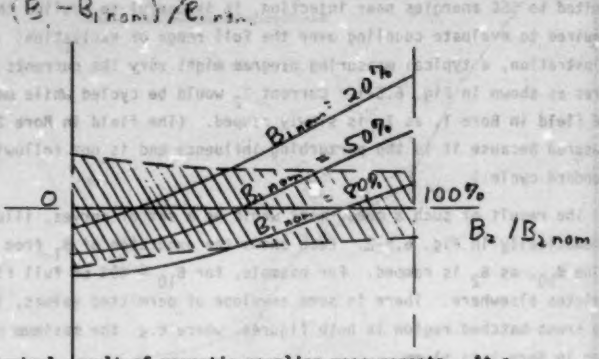

Fig. 6.5-2. Typical result of magnetic coupling measurements. At a fixed $B_{1\,nom}$, the actual field in Bore 1 is measured as a function of B_2. Curves cross the axis at $|B_2| = |B_1|$. The cross-hatched area indicates acceptable coupling.

Appendix 6.6

COUPLING BETWEEN DESIGN D MAIN DIPOLES

The body leakage has been calculated for four cases: both rings at full field (taken to be 6.1 T), both at 20% of full field, and both arrangements of unbalance in a 5:1 ratio with the higher-field bore at full field. An over-under configuration (top-bottom) is assumed, in accord with current plans for Design D. The distance between the beams was taken to be 24 inches (61 cm), the diameter of the cryostat and therefore a minimum value.

In the usual units (harmonics at 1 cm radius in parts per 10,000 with respect to the dipole field), the 5:1 unbalance changes the dipole field by 1.6 units, the quadrupole field by 0.05 units, and the sextupole by 0.03 units. Higher order terms are less than 0.02 units (consistent with zero). These couplings are probably small enough to be satisfactory. Ring-to-ring coupling with a 1 TeV-5 TeV unbalance will be much lower still, since the leakage declines sharply below full field. Plots of the field lines for two of the cases are shown in Figs. A6.6-1 and A6.6-2. (Note that harmonics are evaluated at 0.5" and that N=1 corresponds to the dipole term.)

For the calculation of the coupling between the ends, a constant-perimeter end in the GFUN program was used as an approximation. The harmonics due to one end were referred to a 30"-long dipole straight section, which had an iron arrangement as shown in Fig. A6.6-3. The cylindrical iron yoke of the affected magnet was approximated with a square due to limitations in the configurations allowed by GFUN. No iron was over the ends, which are sketched in Fig. A6.6-3. In this calculation, the leakage field from the end changes the dipole by less than 1 part in 100,000 and changes the multipoles by less than 0.01 unit. This is satisfactorily small.

Table A6.6-1

Coupling between design D main dipoles (over-under arrangement).

Body Leakage (POISSON runs)

Case		α		β	
Aperture		Top	Bottom	Top	Bottom
Excitation (kA-Turns)		432	-432	86.4	-432
Harmonics at 0.5 in.	N	BN(kG)	BN(kG)	BN(kG)	BN(kG)
(Dipole)	1	61.539	-61.539	12.416	-61.549
	2	-.004	.006	-.001	.005
	3	.062	-.062	.017	-.062
	4	-.003	.003	-.001	.003
	5	-.403	.403	-.081	.403

Case		γ		δ	
Aperture		Top	Bottom	Top	Bottom
Excitation (kA-Turns)		432	-86.4	86.4	-86.4
Harmonics at 0.5 in.	N	BN(kG)	BN(kG)	BN(kG)	BN(kG)
	1	61.548	-12.416	12.416	-12.416
	2	-.001	.001	-.001	.001
	3	.062	-.017	.017	-.017
	4	-.003	.001	-.001	.001
	5	-.403	.081	-.081	.081

Differences in indicated channel at 0.5 inches:

Excitation	100%		20%	
N	BN(α-γ)	BN(α-β)	BN(δ-β)	BN(δ-γ)
1	-0.00981	0.00970	0.00003	-0.00003
2	0.00036	0.00030	0.00000	0.00000
3	0.00031	-0.00032	0.00000	0.00000
4	-0.00002	-0.00002	0.00000	0.00000
5	0.00000	0.00000	0.00000	0.00000

Note that the 20% excitation channel has the same multipole set independently of the excitation in the other channel. Hence there is essentially no coupling into the low excitation magnet.

Differences in the indicated channel at 0.5 inches referred to say 61.54 kG for the high excitation channel and 12.42 kG for the low excitation channel.

Excitation		100%		20%	
	N	RN(α−γ)	RN(α−β)	RN(δ−β)	RN(δ−γ)
(Dipole)	1	-0.000159	-0.000158	0.000002	0.000002
	2	0.000006	-0.000005	0.000000	0.000000
	3	0.000005	0.000005	0.000000	0.000000
	4	0.000000	0.000000	0.000000	0.000000
	5	0.000000	0.000000	0.000000	0.000000

End Leakage (GFUN constant perimeter end #5) (no iron over ends)

Integrated Bending Field (GFUN). Magnet Half Length = 30 in.

X (in.)	Y (in.)	Channel 1 (G-in.)	Channel 2 (G-in.)
-1.00	0.00		104
0.00	0.00	1,868,875	113
1.00	0.00		104

The effective half magnet length is 30.368 inches. Thus the effective half length of a 480 inch magnet is 240.368 inches. In addition since the end fields from channel 1 do not reach into the body of channel 2 the integrated fields in channel 2 remain constant as the magnet length is varied. Hence for a 480 inch long magnet the integrated harmonics associated with one half the magnet are:

Excitation Harmonics at 0.5 inches	N	Channel 1 100% BN(kG-in.)	Channel 2 0 BN(kG-in.)
(Dipole)	1	14792	.11300
	2		.00000
	3		-.00225

Since saturation effects do not alter the end leakage appreciably the following coupling table may be constructed from the previous table by assuming that the integrated field is proportional to the excitation.

End leakage harmonics at 0.5 in. Half magnet length of 240 in.

Channel	Excitation (percent) 1	2	$\int H_y dz$ 2	End Leakage (kG-in.) 2 from 1	Normalized Harmonics R1 2 from 1	R3
	100	100	14792	0.1130	0.00000764	-0.00000015
		20	2958	0.1130	0.00003820	-0.00000076
		5	740	0.1130	0.00015279	-0.00000304
	20	100	14792	0.0226	0.00000153	-0.00000003
		20	2958	0.0226	0.00000764	-0.00000015
		5	740	0.0226	0.00003056	-0.00000061

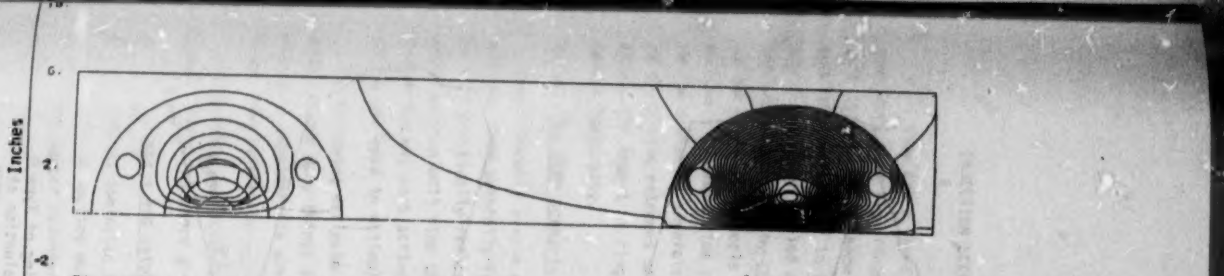

Fig. A6.6-1. Field line plot for Type D magnets, with the right bore at full excitation (6.1T) and left bore at 20% of full excitation.

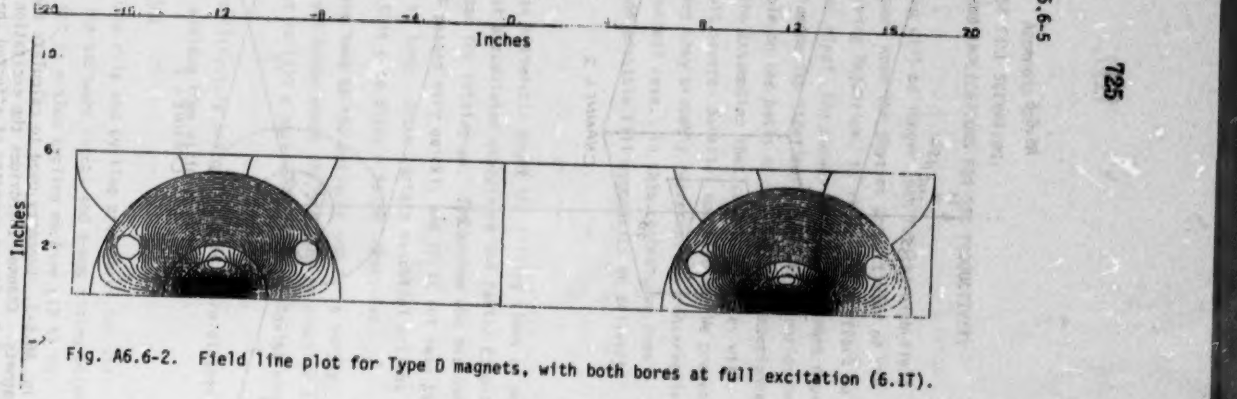

Fig. A6.6-2. Field line plot for Type D magnets, with both bores at full excitation (6.1T).

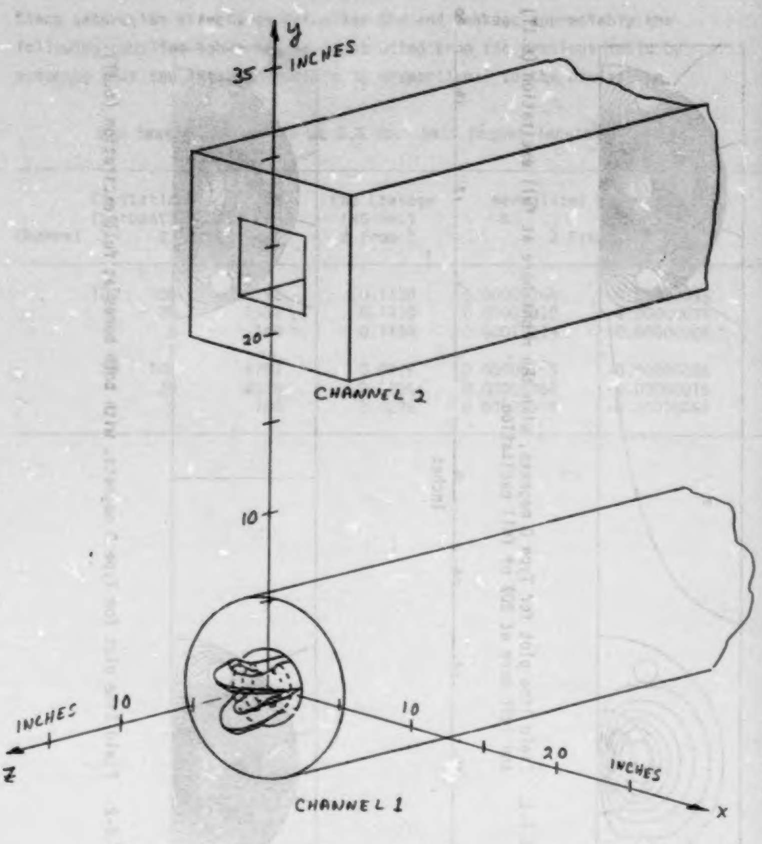
y
35
INCHES
20
CHANNEL 2
10
INCHES
10
10
20
INCHES
Z
CHANNEL 1
X

Fig. A6.6-3. Geometry used to calculate end coupling of Type D magnets. Channel 1 provides the excitation for evaluation at Channel 2. Square geometry of affected channel is due to GFUN program limitation.

Appendix 6.7

SSC FILL SCENARIOS:
INJECTION SCENARIOS AND IMPLICATIONS FOR SSC PRODUCTIVITY

Fill time for a low-field ring will be longer than for the high-field ring; does this significantly impact upon the physics productivity of the SSC? In the case of beam loss during injection, is it worth the effort to keep the beam already in the other ring? The answer to such questions depends upon fill time as scaled by the luminosity lifetime. Two fill scenarios have been worked out, one by CERN people on the basis of ISR and $S\bar{p}pS$ experience, and one by SSC/CGD people under the assumption that control advances will decrease assessment time and permit several parallel operations. We present the two scenarios separately, since they probably represent the conservative and optimistic extremes of the eventual case. In this context, we then analyze the impact of ring size and possible fill gymnastics on delivered average luminosity.

A6.7.1. The CERN scenario

Understandably people are often optimistic about the filling times of new machines. One naturally feels that accumulated experience and faster computers will drastically reduce the time for setting-up. Yet anyone who has operated a machine will find that time passes very quickly and it is not easy to account for why each action takes so long. Often certain essential actions are not included in estimates and this also gives a false impression.

The following estimate will seem long to the optimist and it is surely naive because many things are not yet known about the SSC, but in practice it would be a considerable achievement to fill a machine of such complexity within the time indicated.

All actions are assumed to be satisfactory and not to need extra diagnosis or work. This therefore gives the minimum time estimate.

1. Cycle and setup (45 min)

This is dominated by the ramp rate and cycling procedures for the superconducting magnets. The software checks and dummy timing pulses may appear redundant, but SSC is a slow cycling machine (12 h) so that equipment will be switched off and on, the injector will have been serving other users and many conditions could have changed. It would be unwise to skimp on these checks, since the time penalty for quenching a magnet is high. However, we assume all checks are positive or can be corrected in parallel without loss of time.

(a)	Assume magnet is at maximum field from previous coasting beam run (i.e., no access time). Cycle 100% → 0% → Injection settings	20
(b)	Set auxiliary windings	5
(c)	Set auxiliary magnets (done in parallel)	--
(d)	Software checks	5
(e)	Set up RF	10
(f)	Dummy timing pulses	5

2. Set up injection (22 min)

The two rings cannot be set up in parallel, since the injector must have its polarity reversed. No time has been allowed for this reversal as no information is available. It will be added as an unknown overhead at the end.

(a)	Low intensity pilot pulse to check overall transfer between machines and final storage without risk of quenching, in first ring (Cycle time 45 s ≈ 1 m.)		1
(b)	Medium intensity pulse to measure closed orbit and correct it		
	Request time	15 s	
	Cycle time	45 s	
	Calculation	15 s	
	Display with operator value assessment and check for malfunction	15 s	
	Application	15 s	
	Dead time to next cycle request	15 s	
		120 s	2

(c) Medium intensity pulse to check orbit correction and to measure injection error on new orbit and to apply correction 2

(d) High intensity pulse to check injection error correction and to be stored for next stage 2

(e) Two more pulses injected ready for next stage 4

(f) Injector reversal time —

(g) Repeat for second ring after injector is reversed (Keep both beams for next stage) 11

3. Separate beams (15 min)

The three pulses left in the first ring will now have been circulating for some time and will give an accurate value for the lifetime, which will be a good indicator of the "health" of the machine.

(a) Wait an additional time for an approximate lifetime value from the second ring 1

(b) Perform a luminosity measurement by moving the beams through each other with local bumps. This gives accurate relative beam positions at the crossing points so enabling the beams to be separated in a precise manner. This is luminosity limited not computer limited. The three pulses in each ring will enable all six crossing points to be monitored. 14

4. Filling (38 min)

(a) Displace pulse across aperture to measure central orbit tunes and chromaticity (both rings in parallel) 3

(b) Move pulse across aperture until losses are seen to establish available space. (Both rings parallel) 3

(c) Inject for RF set-up and pre-acceleration checks 4

(d) Fill first ring (15 pulses x 45 s) 12

(e) Time to reverse injector —

(f) Inject for RF set-up and pre-acceleration checks 4

(g) Fill second ring 12

5. Accelerate (15 min)

Ramp time with rings in parallel. Intermediate stops for checks would be advisable, but are not included. 15

6. Low-betas (15 min)

The exact procedure for switching on low-beta insertions will depend on the optics and the power supplies. A continuous optics solution from off to fully on and power supplies that control adequately at zero current would allow the insertions to be applied from zero to full strength at the maximum energy. Alternatively the insertions would be ramped with the main field and then at the top energy they would probably be powered even further to squeeze the betas to their minimum values. The difference, however, is probably not a critical one for these time estimates. The number and power of the low-betas will require that some care is taken in their application, since small alignment errors in these strong quadrupoles will strongly affect the closed orbits.

Ramping all low-betas in parallel with two or three intermediate stops for closed orbit and tune checks 15

7. Experimental magnets (15 min)

Ramping experimental magnets (almost certainly also superconducting). Application of closed orbit corrections around experimental magnets, coupling correction etc. if needed 15

8. Luminosity steering (15 min)

The steering and beam separation made before acceleration will certainly have been perturbed by the changes in machine optics made during and after acceleration. In addition, the luminosity monitor constants depend on beam geometry, e.g. crossing angle changes due to the field of an experimental magnet. For these reasons a second luminosity measurement and optimization is usually needed with positioning of the interaction point in both transverse planes and longitudinally via RF timing 15

9. Adjustments (30 min)

Once all measurements, optics changes and beam steering have been done, the beams must be put into the best and safest condition for physics. Firstly collimators are added to protect equipment from beam losses. To improve lifetime and loss rates, which means physics background, Schottky measurements of the tune values are taken and a correction is applied mainly for beam-beam effect. Also betatron coupling should be minimized using the beam transfer function. 30

10. Contingency (30 min)

(a) It is unreasonable to expect all systems to function perfectly in a machine with the complexity of the SSC

(b) Certain actions that will need to be taken have surely been overlooked

(c) The two reversals of the injector polarity will take a finite time, maybe far in excess of this contingency 30

Total 4 h 00

These numbers are summarized in Table A6.7-1, where we also estimate the refill time after an incident (e.g., injection quench) which leaves beam in one ring.

Table A6.7-1

SSC Warm Fill* and One-Beam Re-Fill Time Estimates

	Fill both rings	Re-fill single ring
1. Cycle and set up	45	30
2. Set up injection	22	10
3. Separate beams	15	-
4. Fill	38	25
5. Accelerate	15	15
6. Low Betas*	15	30
7. Experimental magnets*	15	30
8. Luminosity steering	15	15
9. Adjustments	30	15
Minimum time	3 h 30	2 h 15
10. Contingency	30	30
Totals	4 h 00	3 h 20

*Assuming parallel manipulations in all IR's

A6.7.2 The optimistic scenario

The CERN people have emphasized the importance of detailed checks, adjustment, and evaluation at each stage of the fill process, both to achieve efficient operation and to avoid quenches. They assume advanced computer methods throughout. Nonetheless, how short can t_{fill} be if one must deal only with limits imposed by intrinsically "slow" time constants, such as ring rampup times and times required to optimize luminosity and reduce noise? Our results under this scenario are presented in Table A6.7-3.

We assume the models given in Table A6.7-2, where the only differences between the two machines is n_H, the number of high energy booster (HEB) pulses necessary to fill the main ring (MR). We also define

t_L = Time required for the low energy booster (LEB) cycle.

t_H = Time to accelerate and extract the 1 TeV beam from the HEB, and to ramp back down to prepare for the next pulse.

The the time required to fill the MR is

$$t_{fill} = n_H(t_H + n_L t_L) \quad .$$

Table A6.7-2
Model for fill time assessment.

	6T	3T
Main ring circumference	90 km	160 km
HEB circumference	6 km	6 km
LEB circumference	1.2 km	1.2 km
$n_L = \frac{\text{LEB pulses}}{\text{HEB fill}}$	5	5
$n_H = \frac{\text{HEB pulses}}{\text{MR fill}}$	15	27

On the basis of Tevatron experience, we estimate t_H = 50 s (30 s up and 20 s down), and estimate t_L = 5 s. Then

$$t_{fill} = n_H \times 75 \text{ s} \quad .$$

It then takes 19 m to fill one ring of the 90 km machine, and 34 m to fill the 160 km machine.

We assume that the 20 TeV beams are rampped down before abort, so that essentially the rampup time of 1000 s, including cycling, is required. During this long time all preparation for injection by the rest of the system is completed, including preparation of a "practice pulse," a low-intensity pulse which tests the injection line and ring configurations. It is assumed that verification is fast, and that MR filling can start after a short time. The rest of the scenario goes as shown in Table A6.7-3. The one case in which we were not optimistic concerned the period in which beams were collided, luminosity maximized, and low noise running conditions established. The final estimate is just over two hours for the 90 km ring, and a half hour longer for the 160 km ring.

A6.7.3 The impact of fill time on SSC operations

It has been estimated in the preceding sections that from two to four hours will elapse between the termination of an SSC run and the start of a new one. A luminosity lifetime of 14 to 24 hours may be expected, depending upon the time evolution of the emittance. Under these conditions, should efforts be made to decrease the fill time? The answer seems to be that improvements in the average luminosity will be sufficiently modest that substantial effort is not justified.

We may model the problem in a simple way by assuming a constant (!) time t_{fill} between runs, followed by colliding beams with profile $L = L_0 \exp(t/\tau)$. After a time T, chosen to maximize the average luminosity, the run is terminated. Using the scaled variables $x = T/\tau$ and $y = t_{fill}/\tau$, the average luminosity is

$$<L> = L_0(\frac{1 - e^{-x+y}}{x}) \quad ,$$

which goes through a rather flat minimum at $(1 + x)\exp(-x) = \exp(-y)$. The solutions for optimal run time and $<L>/L_0$ are shown in Fig. A6.7-1. Rough operating points for CESR, PEP, the ISR, and the $S\bar{p}pS$ are indicated by circles. The first three machines in fact operate at close to the conditions expected from this model.

The $S\bar{p}pS$ is a special case, because of the long time required to accumulate antiprotons. From Appendix 6.12 we obtain $\tau = 15$ h, $t_{fill} = 6$ h, $T = 24$ h, and $<L>/L_0 = 0.29$ (for 1983-84). The point $(t_{fill}/\tau, T/\tau)$ falls considerably above the optimal curve. If T/τ were at the optimal value (1.18), then $<L>/L_0$ would be 0.46; for the actual value ($x = 1.6$), $<L>/L_0$ is 0.44. In contrast, the achieved $<L>/L_0$ was 0.29, 67% of the "trouble-free" expectation. (The

Table A6.7-3

"Optimistic" warm refill scenario.

Procedure			Time estimate	
Main Ring	HEB + inj. lines	LEB +inj. lines	90 km	160 km
Run down exp. dipoles, turn off low β^* optics, decelerate, abort, cycle magnets	Terminate physics ←——Fill with practice pulse——————	Same	1000 s = 17 m	
Practice pulse			2 m	
Fill one ring		70 s × n_H	19 m	34 m
	Reverse HEB and injection lines; cycle	Reverse injection lines	2 m	
Practice pulse	←—————————————————		4 m	
Fill other ring			19 m	34 m
Accelerate	Standby	Standby	17 m	
Collide; turn on exp. dipoles, low β^* optics, steer for low noise, maximum luminosity	Standby	Standby	45 m?	
			2 h 5 m	2 h 35 m
Physics	Resume physics	Resume physics?	About 10 h	

achieved $<L>/L_0$ was not available for the other colliders, and we have no PETRA data.)

For small y, i.e. fill time short compared with the lifetime, one should fill very frequently---before the beams have decayed substantially. In a real situation one would fill less often because of a variety of risk factors, so that the turnup in the average luminosity which appears at small y is not realizable.

It is interesting to note that only for $t_{fill} > 0.7183\tau$ does one keep the beams for as long as a decay time, and that if $t_{fill} > 0.3068\tau$ one always dumps more than half the accelerated beams. For y = (4 h)/(20 h), 56% of the injected beams are dumped every 15.4 h. Of this time, 11.4 hours is available for physics

In Table A6.7-4 we list results for the range of refill times and lifetimes discussed in the preceeding sections. Optimal times for a full cycle (refill-physics-dump) range from 9 to 17 hours, and one should realistically expect to refill every 12 hours. $<L>/L_0$ should be taken as an overall machine efficiency. It ranges from 51% to 68%. The derivative of efficiency with fill time is small enough that a scenario which saves an occasional half hour (like saving one beam after a quench results in a lost beam in the other ring) is not worth heroic effort.

On the other hand, the extremes in estimated refill time imply a 14% difference in overall efficiency, depending only slightly on luminosity lifetime. Decreased refill time is clearly worth the effort.

With the model given above, a 3T ring requires an extra 30 m of fill time, simply because it takes about 12 extra HEB cycles to fill the extra 70 km of ring. The efficiency penalty ranges from 4% to 6%, depending upon refill time and luminosity lifetime. On the surface, a systematic 5% efficiency penalty over the lifetime of the machine would argue against the large ring. However, the problem vanishes if the model is slightly changed: Also scale the HEB and LEB by the same circumference ratio. The efficiency benefit would certainly justify the rather small cost differential.

Table A6.7-4

Optimal run time solutions for fill times and luminosity lifetimes discussed in sections A6.7-1 and A6.7-2.

	t_{fill}	y	x	T	$\langle L\rangle/L_0$	$\left(\frac{\langle L\rangle}{L_0}\right)^{-1} \frac{d}{dt_{fill}} (\langle L\rangle/L_0)$
14 h	4.0 h	0.286	0.958	13.41 h	0.511	-7.46%/h
14 h	3.33 h	0.238	0.857	12.00 h	0.539	-8.34%/h
14 h	2.0 h	0.143	0.634	8.88 h	0.612	-11.27%/h
14 h	2.5 h	0.179	0.723	10.12 h	0.580	-9.88%/h
24 h	4.0 h	0.167	0.693	16.63 h	0.591	-6.01%/h
24 h	3.33 h	0.139	0.624	14.98	0.616	-6.68%/h
24 h	2.0 h	0.083	0.466	11.18	0.682	-8.95%/h
24 h	2.5 h	0.104	0.528	12.67	0.655	-7.89%/h

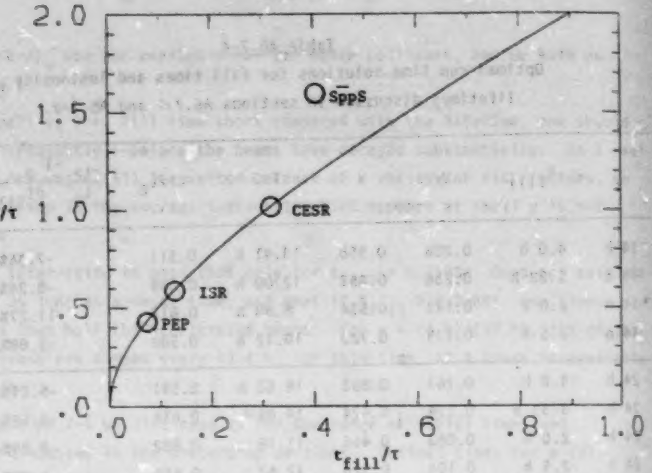

Fig. A6.7-1(a). Optimal time between fills as a function of fill time scaled by luminosity lifetime.

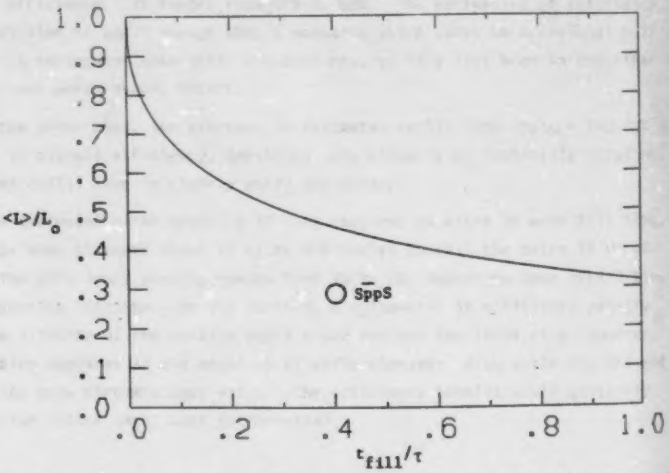

Fig. 6.7-1(b). Optimum machine efficiency (average luminosity divided by peak luminosity) as a function of scaled fill time.

Appendix 6.8

MAGNET REPLACEMENT AS A FUNCTION OF PROPOSED MAGNET STYLE

Magnet changes may be divided into two categories: (a) replacement of magnets which are found not to meet specifications on initial cooldown, or fail shortly thereafter, and (b) replacement of magnets which fail during late commissioning and operation periods. The former has little impact upon other activities, and the main penalty is in the labor cost of the replacement (including appropriate support personnel, indirect costs, etc.). In the latter case, all costs of the laboratory go on, mostly unproductively, while the replacement takes place. In Appendix 6.11 the laboratory operating cost is estimated at something in excess of $600K/day. A seven-day replacement thus "costs" $4.2M, so that actual labor costs are insignificant. In both cases the capital cost of the magnet is lost, but although this is the dominant cost in the installation case and does depend upon magnet style, its effect is not within the scope of this report.

Table A6.8-1 shows a step-by-step scenario for replacement of four styles of magnet in the SSC. It includes all appropriate steps used for the Tevatron, foreseen for CBA, and used in assembly of the CBA Full Cell. The CBA assembly is especially appropriate because it involved cold iron one in one magnets with all welded connections, with three high current and 42 trim leads. Time estimates are given for each step, using the rationales given below. These are consistent with Tevatron experience for which actual times are shown. Adhering to these times will require: 1) excellent organization, with each participant ready for his cue, and 2) well-practiced procedures executed with no mishaps. All of the times assume separate crews working simultaneously at each end of the magnet wherever appropriate.

1. Diagnose problem. This means detecting the problem and isolating it to a single specific magnet. The time in the table is based upon Tevatron experience.
2. Warm-up. Electrical warm-up heaters are assumed for D and A. The type D dipole requires 7 kW for warmup in three shifts. A half-cell consists of 5 dipoles plus a quad and a spool piece--call this 6 dipoles equivalent. It would be necessary to locate a 440 V outlet

with 42 kW capability, or 95 A, every 100 m. This is ~50% more than the typical welding outlet requires, and might add ~$250K to the cost of the machine. Magnet A would require ~150 A per outlet, adding ~$500K over D.

3. Spoil vacuum. This means letting the insulating and beam tube vacuum up to atmospheric pressure, using dry nitrogen.
4. Disconnect magnet. Style D takes longer than Tevatron magnets because of the all-welded construction. The two "dual" designs take even longer because there are more things to disconnect.
5. Remove bad magnet. The time is the same for all the "short" designs, but significantly longer for the 140 m design.
6. Prepare for new magnet. Vacuum and single phase He enclosures must be cut back, and pipe ends must be prepared for welding (chamfered, old weld metal ground off, etc.). The reason for differences is the same as in (4).
7. Place new magnet. Difference same as in (5).
8. Align magnet. This is judged to be a relatively simple job for the short magnets and 5-10 times more time consuming for design C, which is ~10 times longer.
9. Connect electrical. High current and trim leads must be soldered together as appropriate and the correctness of connections verified. It is assumed that the total time required for each high current lead is one hour, and for each trim lead is ten minutes. These are shorter times than are achieved at CBA, but are feasible. The corresponding times for the Tevatron are 4-5 minutes for a low current (voltage tap) lead and 45 minutes for a high current cable. For design C, the magnet will have between 16 and 320 trim leads, depending on where it is located in the string, giving the range of times shown.
10. Connect mechanical. All pipes and enclosures must be rewelded, and shield sections and superinsulation reinstalled. The same number of

helium pipes (4) is assumed for each design (in addition to the single phase helium pipe), but the two dual designs have two beam tubes. The vacuum enclosure in A is much larger than in D, and in C is smaller than D.

11. Pump down. Both insulating and beam vacuums must be reestablished, and the time is completely dominated by the time required to obtain beam tube vacuum. If the 0.5 shift quoted for the Tevatron is taken as the basis, and the pumpdown times are scaled linearly with the length of the pumped section (1/2 cell) and inversely as cube of the diameter, the calculated times are unacceptably long.

    We consequently took another approach. A twenty-four hour (three shift) pumpdown time was allocated for each magnet style. The calculated average beam tube pressure at the end of this period was 6.7×10^{-5} Torr for the 3T design and 2.4×10^{-5} Torr for both 6T designs. (See Appendix 7.3)

12. Leak check. This scales very roughly as the total length of weld to be checked.

13. Hi-pot warm. This is figured as 0.1 shift for setup time plus 0.01 shift/lead.

14. Cool down. Various calculations agree on a cooldown time of three shifts for design D. The other times are scaled (from D) linearly with the cooldown mass and (very roughly) inversely with the helium mass flow available for cooling.

15. Pre-start checkout. Time per beam based on Tevatron experience.

Table A6.8-1
Magnet change scenario
Elapsed time in shifts (people)

STEP	TEVATRON	Dual 2-in-1 6T("A")	No-iron 1-in-1 5T("B")	Dual 3T("C")	1-in-1 6T("D")
1. Diagnose Problem	2.0	2.0	2.0	2.0	2.0
2. Warm-up Stage Move Spare Equipment into place (dominated by warm-up)	3.0 (5)	3.0 (5)	3.0 (5)	3.0 (5)	3.0 (5)
3. Spoil Vacuum	0.1 (2)	0.1 (2)	0.1 (2)	0.1 (2)	0.1 (2)
4. Disconnect Magnet	0.1 (2)	0.3 (4)	0.1 (4)	0.3 (4)	0.2 (4)
5. Remove Bad Magnet	0.1 (3)	0.1 (3)	0.1 (3)	0.1 (10)	0.1 (3)
6. Prepare for New Magnet	0 (0)	0.3 (4)	6.2 (4)	0.3 (4)	0.2 (4)
7. Place New Magnet	0.1 (3)	0.1 (3)	0.1 (3)	0.3 (10)	0.1 (3)
8. Align Magnet	0.1 (2)	0.1 (2)	0.1 (2)	0.5 (2)	0.1 (2)
9. Connect Electrical (Include Verification	0.3 (4)	1.6 (4)	0.8 (4)	3.6- (4) 9.9	0.8 (4)
10. Connect Mechanical		0.7 (4)		0.4 (4)	0.4 (4)
11. Pump Down (Dominated by beam tube)*	0.5	3.0	3.0	3.0	3.0
12. Leak Check	0.5 (3)	1.0 (3)	0.6 (3)	0.8 (3)	0.7 (3)
13. Hi-Pot Warm	0.3 (2)	0.5 (2)	0.3 (2)	1.7 (2)	0.3 (2)
14. Cool-Down (also, remove old magnet and Equip. from tunnel and clean-up)	3.0	3.0	3.0	4.5	3.0
15. Pre-start Checkout	0.2	0.4	0.2	0.4	0.2
TOTALS (Shifts)	10.3	16.2	13.6	21.6-28.2	14.2
TOTALS (Days)	3.4	5.4	4.5	7.2- 9.4	4.7

*Defined to be 24 h for SSC magnets.

Appendix 6.9

ACCELERATOR STUDIES DURING REPAIR PERIODS ASSUMING TWO INDEPENDENT RINGS

The purpose of this section is to estimate how much accelerator study time could be gained by having the two rings of magnets as cryogenically and magnetically independent as possible.

At a typical accelerator laboratory (e.g., CERN, BNL, FNAL) approximately 20% of machine time is devoted to studies and machine experiments after the initial commissioning period. These studies obviously reduce the time available for high energy physics experiments.

Assuming that one ring is unable to accelerate or coast beam because of an equipment failure but that the other ring can still operate with beam, some examples of useful one-ring beam studies are:

1) Injection studies.
2) Orbit correction (correction dipole adjustment).
3) Aperture scans.
4) Tune measurement and adjustment.
5) Chromaticity measurements and adjustment.
6) Acceleration studies.
7) Coherent effects (i.e., single beam-wall effects, measurement of impedances).
8) Skew coupling measurements.
9) Resonance compensation.
10) Beam emittance as a function of energy.
11) Phase space dilution.
12) Abort system tuning.
13) Low beta studies.
etc.

There are many more of course. These measurements are a necessary part of commissioning and will be made again and again as improvements are installed in the machine.

Another case involves equipment tests. Some examples are:

1) Refrigeration measurements.
2) Power supply ripple and regulation measurements.
3) Controls diagnostic tests.
4) Quench recovery optimization.

A third class of experiments is not relevant to this discussion because both beams would be required (e.g. beam-beam effects, luminosity measurements, etc.)

In order to get an idea of the "free" accelerator study time that would be made available, we used the Tevatron down-time log for the month of February, 1985.

The results are shown in Table A6.9-1.

Table A6.9-1

Tevatron Downtime
Feb. 1 to Feb. 28, 1985
(436 Hours of H.E.P. Scheduled)

Tevatron System	Hours Down	%H.E.P. Lost
Controls	8.05	1.85
Vacuum	0.10	0.02
Magnet	0.0	0.0
Cryogenics	15.20	3.49
RF	1.23	0.28
Power Supply	5.78	1.33
Correction System	4.33	0.99
Quench Protection Sys.	8.17	1.87
Injection System	6.94	1.59
Quenches	25.81	5.92
Misc.	9.78	2.24
Total	85.39	19.58

There were no problems that required tunnel access during scheduled running time. There were two days set aside every other week for routine maintenance when tunnel access was permitted. COMMENT: Downtime intervals ranged from a minute or so (for example, to re-boot a computer) up to about 4 hours (to fix the injector kicker electronics). The shorter periods are probably useless for studies; however, there were 58 incidents where the machine was off for one-half hour or longer. These were times when single machine studies could have been conducted in the hypothetical second ring. These longer intervals totaled 58.4 hours, consuming 13% of the scheduled high energy physics running time. In other words, if the two rings were to be built of uncoupled magnets, one could predict, based on this sample of Tevatron data, that about half of the one-ring accelerator study time would come without additional penalty to the physics program.

One necessary caveat concerns the fact that during many of the down periods the machine was imminently expected to be up, so that only in retrospect was there a machine physics opportunity. Even if half of the incidents were in this category, there would be a 7% "bonus" of useful time for studies, and a consequent 7% increase in physics productivity.

Other scenarios are also possible. For example, a Tevatron shift was recently lost while the refrigerator was repaired. In the SSC situation, one but not both rings could be powered during the scheduled outage of a refrigerator. In this case and others like it, one-beam machine studies would be scheduled.

Appendix 6.10

MAGNET FAILURES AT t = 0: COST PENALTIES AND DESIGN CHOICES

A6.10.1 Introduction

The first production SSC magnets magnets will be completely tested at 4.5 K. During later production a sample will be cold-tested in order to monitor quality control. But what fraction should in principle be cold-tested in a factory setting, given the relative difficulty of removing a failed magnet in the tunnel? More to the point of this report, are the conclusions impacted by the choice of magnet design?

The answer seems to be that if the tunnel replacement times given in Appendix 6.5 are anywhere near right, and if failure rates are acceptably low on the basis of other criteria, then one does minimal factory cold-testing. A more detailed in-tunnel change scenario could alter this conclusion, but only if gross underestimates have been made. In addition, there is a capital cost penalty associated with two-in-one designs, related to the fact that the t = 0 failure rate of such magnets will inevitably be higher than that of one-in-one magnets.

The analysis goes as follows: Let us define

c = Cost of cold-testing a magnet at the factory
C = Cost of replacing the magnet if it fails to operate properly in the tunnel
f = Fraction cold-tested at the factory
F = Fraction needing replacement after cold-testing in the tunnel.

With the assumption that magnets which pass factory cold-tests do not fail in the tunnel, the total cost of testing and failure replacement is

$$\text{Total cost} = fc + F(1 - f)C \quad .$$

This result is linear in the fraction tested, as shown in Fig. A7.10-1. The minimum cost therefore depends only upon whether the slope is positive or negative, and the condition for cold testing in the tunnel (f = 0) is simply that $F \approx c/C$. For example, if it is ten times more costly to cold-test in the tunnel as in the factory, then one should do so if the failure rate is less than 10%.

Our remaining task is to estimate c, C, and F.

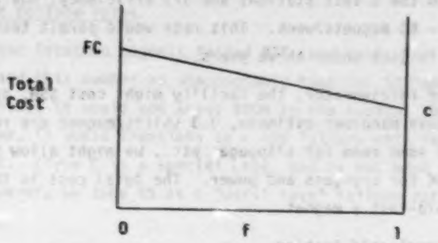

Fig. A6.10-1. Total cost of eliminating failed magnets at t = 0.

A6.10.2 Cost of factory cold-testing.

All Tevatron magnets were cold-tested in the Fermilab magnet test facility (MTF). This experience forms the basis of the present estimate.

During normal cold-testing, a number of different problems were found: Coil problems which developed only on cooldown, magnets which could not reach the design current after normal training, and inconsistent or unexplained behavior. In some cases field quality was measured on cold magnets, but in the present context we assume these measurements to be unnecessary. Warm testing will in any case have already been done at the factory.

The Tevatron cold-test facility cost \$3M to \$4M. It had 6 test stations, tested 2 dipoles + 1 quadrupole per day, and employed 50 people. This throughput included warm test procedures which will have been done elsewhere for the SSC magnets. For present purposes, Ray Hanft (Fermilab) has made the following estimate: Assume the MTF is used to test SSC magnets in an expeditious manner. A shift requires 2 measurers, 1 or 2 refrigeration techs, and about 3 techs to install/de-install magnets. For round-the-clock operation we need 4 shifts--30 people in total, plus perhaps 10 supervisors and support people.

Then if we cool in 6 hours (which requires a big refrigerator and lots of liquid nitrogen), quench test for 4 hours, warm for 10 hours (by spoiling the vacuum and electrically heating the coil in a controlled way), and change to the next magnet in 4 hours, the cycle for the two dipoles + one quad would take 24 hours. With the 6 test stations and 5/7 efficiency, the throughput would be 6 x 2 x 5 = 60 magnets/week. This rate would permit testing the 8000 one-in-one magnets in just under three years.

Given the larger refrigerator, the facility might cost \$5M, or \$1.6K/magnet. According to the above manpower estimate, 3.3 shifts/magnet are required, or about \$0.66K. With some room for slippage, etc., we might allow \$1K for manpower, and say \$0.4K for cryogens and power. The total cost is then close to \$3.0K to factory cold-test a magnet.

A6.10.3 Cost of tunnel cold-testing.

In the most pessimistic (and undesirable) scenario, an entire sector of 4000/12 = 330 magnets is tested at once. If the failure rate is 5% (see below), then 17 ± 4 bad magnets must be located and replaced. A few coil problems will be found by hi-potting, but the usual problem will show up as a low-current quench of the weakest magnet. Only after it is replaced can one hunt for the next weakest magnet. The time and manpower estimates made in Appendix 6.5 should apply. About 42 shifts should be required at a cost of \$8.2K, and cooldown of the sector will cost about \$2.5K (50 MW @ \$50). Incidental costs of cryogens, etc. should be added, for a total cost of about \$15K, or about five times the factory test cost.

Although we will use this figure, we regard the procedure as unacceptable. Series replacement of this sort requires over three months for each of 12 x 2 sectors, and would at very least be an enormous distraction during installation. Although much of the work would go on in parallel, it is difficult to imagine that the test/replacement operation would add less than about a year to the time required to bring up the accelerator. A parallel approach is mandatory, and unless it can be devised tunnel cold-testing will be impractical.

There are other objections to tunnel cold-testing which are difficult to quantify, but which argue for factory testing. Welds must be cut, not just on the one or two magnets which might fail in a year, but on 400 or so which might fail upon installation. The workplace will inevitably be cramped and dirty, while the testing and replacement job is one that requires precision and cleanliness.

A6.10.4 Expected failure rates.

About 5% of the Tevatron magnets failed MTF cold-tests for a variety of reasons. We regard this number as unacceptably high for SSC one-in-one magnets. For one thing, it would add about $50M to the capital cost of the magnets. For another, it would translate to a 10% failure rate for an equivalent two-in-one magnet. (Type C is a special case, and is excluded from the present discussion.) However, we take 5% as a "worst case" failure rate for purposes of this Appendix.

An additional 6% of the Tevatron magnets in the ring cannot be ramped higher than 950 GeV. This problem was historical, in that early magnets were made with superconducing cable which was known to be inferior. We assume such problems will not occur for the SSC.

A6.10.5 Tunnel vs. factory cold-testing.

In conclusion, we find $c/C = 0.2$, and require $F < 0.05$ for acceptable magnet production. Other factors aside, the case for tunnel cold-testing is overwhelming: Not unless our cost estimates are in error by a factor of two in opposite directions, AND we reach our uncomfortable upper limit for acceptable failure rates, would the numbers argue for factory cold-testing.

A6.10.6 Magnet design choices.

A two-in-one magnet will fail with twice the probability of a comparable one-in-one. Since the ring would contain twice as many one-in-one's, the expected number of failures would be the same in both cases. With a 5% rejection rate for one-in-one magnets at initial cold testing, we might expect to replace (and essentially throw away) 400 magnets. Since the two-in-ones are nearly twice as expensive, a two-in-one choice would carry with it a 5% capital cost surcharge in $t = 0$ magnet rejection.

Appendix 6.11
SSC OPERATIONS COST

The Operating Cost Subgroup was charged with the task to estimate the yearly operating expenses of the SSC. This was done for the new laboratory, as a whole, and not just for the accelerator costs. We did not estimate the level of funds needed under the categories of Special Process Spares (SPS), Capital Equipment, Accelerator Improvement Projects (AIP), and General Plant Projects (GPP), or the direct costs to support the outside user groups. Outside user staff is not included in the total manpower level.

We assumed, as a model, that the operations cost for a collider laboratory could be separated into the following parts:

A6.11.1 Injector systems.
A6.11.2 Collider systems.
  a. Systems that scale with ring circumference.
  b. Systems that are independent of ring circumference.
A6.11.3 Experimental areas
A6.11.4 Accelerator research and development.
  Experimental facilities research and development.
A6.11.5 Physics research.
A6.11.6 Other:
  Computer operations.
  Central shops.
  Laboratory overhead.

Except for the cryogenics, we estimated the costs for the simplest case of two independent 6 Tesla rings of magnets and for the 3 Tesla cryogenically coupled dual case (see Table A6.11-1). For the injector system costs, we used the present Tevatron complex as a model. We assumed that the Tevatron operated as an injector for the collider and as a source for test beams. We identified the type and number of persons required for each major subsystem as well as the power costs, purchases, materials, supplies, etc.

For the collider, we first identified a unit of scale length that one could scale costs by. We decided upon a unit length of 8 km, a little longer than the present Fermilab Tevatron Ring. This was driven by the refrigerator and power supply placement requirements and our estimate of an acceptable response time to emergency situations by technicians stationed around the ring. For the nonscaling collider systems, experimental areas, computer operations, and research and development areas, we applied the experience of the BNL and FNAL accelerator complexes.

A6.11.1 Injector systems

The present SSC design concept consists of an injector system, not too unlike the present Fermilab accelerator facility. We therefore used the present, FY1985, FNAL Accelerator Division budget as the basis for our estimate. We adjusted the Fermilab numbers downward by the amounts expended to provide a Tevatron physics program. The SSC injector systems would operate as an injector for the collider and as a source of test beams and would not have to provide the scope of beams that the Tevatron presently does. Therefore, the injector system costs from the ion source to the 1 TeV injector for the SSC are less than the present Fermilab complex. We included the manpower, materials, supplies, purchased services, transportation, communication, power costs for the following subsystems:

a. Administration
b. Safety
c. Controls
d. Cryogenic systems
e. Electrical/electronic support
f. Instrumentation
g. Mechanical support
h. RF
i. Injector (linac and booster)
j. TeV injector
k. TeV switchyard and test beams
l. Accelerator operations

We assumed that the injector systems would be running for 325 days each year at a power consumption level of 23 MW. We do not include the building power in this item. This is entered as a separate item.

A6.11.2 Collider systems

The collider systems were broken into two major categories; those that scale with ring circumference; and those that are independent of ring size. The Tevatron experience formed the basis for these estimates.

As was stated previously, we concluded that at 8 km intervals about the collider, one would have to support a cryogenics, operations, and maintenance center. We estimated the number of persons needed to cover the necessary functions of these areas. For the cryogenics systems we applied the industrial manpower practices and costs of the cryogen procedures (see Table A6.11-2). As an independent check of such items as helium consumption, we compared it to the Tevatron experience and found them to be consistent. For the other systems, such as, power supplies, controls, instrumentation, air conditioning, water systems, etc., we estimated the effort as defined by the parameter lists in the Reference Design. Our estimates were made on the basis of the number of control system modules; power supplies, etc. In addition to the distributed area functions, we considered the collider central group costs which entail tunnel maintenance ("tunnel rats") personnel, cryogenics, RF, vacuum, controls, electrical and mechanical support, safety, etc. Special effort was made to understand the impact of ring size to these areas, especially for the "tunnel rats," where the 3 Tesla machine pays a 40% premium over the smaller 6 Tesla machine (see Table A6.11-3) due to additional mobilization and transportation costs.

The extra manpower requirement for the larger ring can be easily understood: a stand-alone building containing some mix of refrigeration and maintenance equipment must be attended by at least two people. If this is to be done for 21 shifts/week, 10 people are required. In our model, there were about 12 extra stations of this kind, in accord with (a) the RDS statement that the 3T ring requires 24 refrigerators, and the 6T only 12, and (b) our model, which puts a premium on fast access and therefore places maintenance personnel every 8 km. The assumpion could be changed for either ring, either in the design stage or after operational experience is gained.

The power usage estimates for the main ring are based on the following assumptions and calculations:

1. Cryogenics. Input numbers are given in Tables A6.11-4 and A6.11-5, where sources and other input data are also discussed. Cryogenic entries to Table A6.11-1 have been multiplied by 1.5 to account for normal inefficiencies. Operation 365 days/yr is assumed.
2. Magnet Power Supplies. Both the Type C and Type D designs use 12 power supplies per circuit, each with a voltage drop of 14 volts. For the 3T design, there are 4 circuits of 11 kA (inner), 10 kA (outer), 2.5 kA (corrections), and 3 kA (quadrupoles). The circuits are configured so that at full field one power supply supplies most of the current, which we take as 12 kA (see Appendix 7.2). The total power consumption is (14 V) x (12 kA + 2.5 kA + 3 kA) x (12 power supplies) x (2 rings) = 5.9 MW. For the 6T case, there is a single 6 kA circuit with 12 power supplies per ring and a total power consumption of 2 MW. We assume the AC power efficiency is 100%. Operation for 325 days/yr is assumed, as is the case with the items below.
3. RF System. Following the detailed discussion of Appendix 7.5,* we take 6 MW as the average RF power of both the 3T and 6T rings. The reasons are quite different, with the 3T machine requiring 24 MW during injection and 3.9 MW during colliding beam operation.

A6.11.3 Experimental areas

We estimated the level of effort to support six large detectors in the intersection regions. We assumed that the intersection regions were equally spaced about the collider. One might be able to reduce the effort a bit if the experimental areas are clustered, although we expect shutdowns will be short and it would be difficult for any given crew to cover more than one experiment. The effort level was developed from the BNL and FNAL fixed target experience and the present estimates for the CDF detector at the Tevatron. The power requirements for the experimental areas assumed a yearly operation of 325 days per year. The RDS power estimate of 5 MW/IR was used.

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*See also Section 5.

A6.11.4 Accelerator and experimental facilities R&D

These two areas include advanced accelerator efforts, machine components R&D, particle detector development, data handling, and advanced computing R&D. We did not itemize in detail each individual area, but instead used the empirical fact that at most accelerators, one invests from 25% to 33% of the total accelerator and experimental areas personnel in research and development, even under relatively static conditions when no major new initiatives are underway.

A6.11.5 Physics research (In-House)

The in-house physics research area was also estimated from the present BNL and FNAL efforts and then corrected for the SSC experimental equipment capital investment. Both the estimated theory and experimental effort reflects our assumption that the SSC will be the major world high energy physics laboratory and for it to be so it must have a first rate physics staff that would be expected to consume approximately 25% of the available beam time. The direct cost of user participation, their support from home institutions, and their periodic presence at the Laboratory are not included in this estimate.

A6.11.6 Other

We separated the computer operations and central shops from other G&A areas, so as to emphasize the importance of these two areas. Computer operations at the SSC will be quite substantial due to the number of users and the volume and complexity of the data that will be generated. We used the present FNAL effort as a model to scale by. We assumed that the technology in the next 5-10 years will reduce the need for operator personnel, but with the increased user population one will require an increase of personnel in the system and user services areas.

We selected a G&A rate of 40% for our estimate. This covers such services as security, fire protection, buildings and grounds, plant engineering, personnel, purchasing, etc.

Ring Size Differential

The operations cost differential between the 3 Tesla and 6 Tesla SSC versions is small within the accuracy of our estimate. Our model assumed the 8 km spacing for refrigerators, power supplies and maintenance centers. The present 3 Tesla design uses twice the number of refrigerators, (each with one-half the capacity), and three times the number of guide field power supplies distributed about the ring, thus preventing consolidation to a 16 km spacing. There are, therefore, differences due to helium make-up and power usage and the number of shift personnel required to maintain this equipment. One also pays a penalty in the size of the "tunnel rat" crews because of travel times for a larger circumference ring, albeit there are 40% fewer corrections packages that have to be serviced. When one considers the entire Laboratory operating cost, the differential operations cost between the two ring sizes is about $20M/y. While this figure is about 10% of our estimated total operating costs, the totals are poorly known, and are regarded as lower limits.

Table A6.11-1
SSC Operations Cost
(FY 1985 dollars)*

Category	Manpower (FTE)	Labor (M$)	Purchases (M$)	Power†	
				(M$)	(MW)
Physics Research	400	16.0	3.1		
Injector Systems	300	12.4	14.8	9.0	23
Collider Cryogenics	85(143)	3.5(6.0)	3.6(4.9)	14.1(16.0)	32.3(36.5)
Collider Other	320(408)	13.2(16.9)	15.0(19.1)		
Magnet Power				0.8(3.5)	2.0(8.9)
RF Power				2.3(2.3)	6.0(6.0)
Misc. Power				0.9(1.9)	2.4(4.8)
Experimental Areas	300	11.0	6.0	11.7	30
Accelerator R&D	100	3.9	3.0		
Facilities R&D	150	5.8	4.5		
Computer Operations	125	5.0	2.5		
Central Shops	100	3.9	1.5		
Building Power				5.2	12
Subtotal	1880(2026)	74.7(80.9)	54.0(59.4)	44.0(49.6)	107.7
G&A (40%)	750(807)	29.9(32.4)	21.6(23.8)		
TOTAL	2630(2833)	104.6(113.3)	75.6(83.2)	44.0(49.6)	
SUM = 224.2 (246.1)‡					

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*Costs for 6 Tesla one-in-one design, with numbers in parenthesis for a 3 Tesla cryogenically coupled dual design.

†Power costs at $50/MWH.

‡This minimal estimate is for a "static laboratory" with no new initiatives and no contingencies.

Table A6.11-2

Collider Satellite Operating Costs: Items that scale per unit length (= 8 km)

	Per Satellite				Ring Total	
Collider Item	Manpower Shift	Shifts	Manpower (FTE)	Purchases ($M)	Manpower (FTE)	MSTC, Power, Purchases ($M)
Cryogenic						
Cryo Field Operator	2/3(2/3)	5	3-1/3(3-1/3)		40(80)	
Maintenance Mech.	1 (1)	1	1 (1)		12(24)	
Maintenance Elect.	1/2(1/2)	1	1/2(1/2)		6(12)	
Maintenance Supv./ Asst.	2/12(2/24)	5	10/12(10/24)		10(10)	
			Helium	0.1(0.1)		1.2(2.4)
			Misc.	0.2(0.1)		2.4(2.4)
General Operations & Maintenance (P.S., Controls, Instrum., Air Cond., Water Systems.....)						
Electronics Tech	1/6(1/6)	5	5/6(5/6)		10(20)	
Electronics Shop	1 (1)	1	1 (1)		12(24)	
Mechanical Shop	1 (1)	1	1 (1)		12(24)	
Mechanical Tech (Use Cryo Group)						
Emergency Response & Security (covered by trained field operators)						
Satellite Field						
Oper. Supv.	1/12(1/24)	1	1/12(1/24)		1(1)	
			Misc.	0.1(0.1)		1.2(2.4)
			8.6(8.1)	0.4(0.3)	103(195)	4.8(7.2)

Numbers in parenthesis are for 3 T cryogenically coupled dual case.
Numbers not in parenthesis are for 6 T one-in-one case

Table A6.11-3

Collider Manpower

Cryogenics-Satellites	68(126)
Cryogenics - General	17(17)
Tunnel "Rats"	135(189)
Operations Support (RF, Controls.....)	120(120)
Machine Operators	30(30)
Satellite (Shift Personnel, Noncryo)	35(69)
TOTAL	405(551)

Table A6.11-4

Steady state heat loads.

	Per Refrigerator				Total			
	6.5T$^{(1)}$ (A)	5T$^{(1)}$ (B)	3T$^{(2)}$ (C)	6T$^{(3)}$ (D)	6.5T (A)	5T (B)	3T (C)	6T (D)
4.5°K (KW)	4.35†	2.05	0.68	2.20	52.2	24.6	16.4	26.4
20°K shield (KW)	--	2.40	1.20	2.60	--	28.8	28.9	31.2
80°K (KW)	20.9	24.0	11.9	24.0	251	288	286	288
Liquid He (liters/hr)‡	210	260	180	340	2532	3120	4320	4080

1. Reference Designs Report.
2. "Refrigeration System for the SSC 3T Cold Iron Magnet System," CCI Report 599-103, 19 March 1984.
3. "Budgeted Heat Loads for Design D," C. Rode, FNAL, unpublished report dated 11 March 1985 (Appendix 4.8 of this report).

*This includes synchrotron radiation, the heat leak of supports, thermal radiation, valves, etc., and 50 watts per interaction region going into each neighboring cryogenic loop.

†The power figure of the RDS for Design A is 4872 watts. This is decreased by 520 watts, and added back as 210 liters/hr of liquid helium for lead cooling.

‡Assumes 0.06 g/s (1.8 ℓ/hr) per kA per lead.
Design D has estimated a total lead cooling (including correction elements) of 4080 liters/hr, corresponding to 2.27×10^6 amps. Of this, 1.15×10^6 amps is due to the main 6 kA power leads, corresponding to 8 power leads per aperture per refrigerator. For Design C, we have assumed six 11 K power leads per aperture per every other refrigerator, plus six 3 kA per source (quads) plus six 2.5 kA per source (quads) plus six 2.5 kA per source (trim) = 2.4×10^6 amps resulting in 4320 liters/hr total. No allowance is made for correction elements.

Table A6.11-5

AC power requirements for main ring cryogenics (MW)

	Carnot efficiency	Fraction of Carnot	Overall efficiency	6.5T (A)	5T (B)	3T (C)	6T (B)
4.5°K (MW)	1.52%	17%	0.25% = 0.387 KW/W	20.2	9.5	6.4	10.2
20°K shield (MW) (from 4.5°K liquid)	1.52%	20%	0.30% = 0.329 KW/W	—	9.5	9.5	—
20°K shield (MW) (from 15°K gas)	5.3%	20%	1.05% = 0.095 KW/W	—	—	—	3.0
80°K (MW)	24%	25%	6.00% = 0.017 KW/W	4.3	4.9	4.9	4.9
Liquid He (MW)		0.83 KW/(liter/hr)*		2.1	2.6	3.5	3.4
Total (MW)				26.6	26.8	24.3	21.5

*CCI Report 593-101 (1 November 1983).

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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0651T

Appendix 6.12

OPERATIONAL ASPECTS OF THE SPS COLLIDER

L.Evans, V. Hatton

ABSTRACT

The SPS now operates routinely for part of the time as a proton- antiproton collider at a centre-of-mass momentum of 630 GeV/c. Over the last four years the peak luminosity has been pushed up by almost two orders of magnitude from $5x10^{27}cm^{-2}s^{-1}$ in 1981 to $3.5x10^{29}cm^{-2}s^{-1}$ in 1984. More important, over the last three years the daily average production (integrated luminosity) has increased by more than an order of magnitude.

In view of the scarcity of antiprotons, the reliability of the whole chain of injectors is of crucial importance. The SPS itself is particularly vulnerable to faults, due mainly to its large size and heavy demands on primary services. In this note, an attempt is made to gather together statistics and data accumulated over the 4 years of operations in order to portray the whole spectrum of problems encountered in running such a large and complicated machine.

A6.12-2

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1. INTRODUCTION

The SPS now operates routinely for part of the time as a proton-antiproton collider at a centre-of-mass momentum of 630 GeV/c. Over the last four years the peak luminosity has been pushed up by almost two orders of magnitude from $5\mathrm{x}10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in 1981 to $3.5\mathrm{x}10^{29}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in 1984. More important, over the last three years the daily average production (integrated luminosity) has increased by more than an order of magnitude.

In view of the scarcity of antiprotons, the reliability of the whole chain of injectors is of crucial importance. The SPS itself is particularly vulnerable to faults, due mainly to its large size and heavy demands on primary services. In this note, an attempt is made to gather together statistics and data accumulated over the 4 years of operations in order to portray the whole spectrum of problems encountered in running such a large and complicated machine.

2. COLLIDER OPERATION

The first proton-antiproton collisions in the SPS were recorded in the summer of 1981. The first physics run took place at the end of 1981, when 0.2 nb^{-1} of integrated luminosity was produced. In the second run at the end of 1982 the peak luminosity was increased to $5 \times 10^{28}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and a total integrated luminosity of 28 nb^{-1} was produced, enough to reveal the first $W^{\pm}$ candidates. In the spring of 1983 the peak luminosity was pushed up to $1.7 \times 10^{29}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and a total of 153 nb^{-1} was produced in each of the two experimental crossings. Finally in the latest run (end 1984) the peak luminosity was further increased to $3.5 \times 10^{29}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and a total of 395 nb^{-1} was produced in each experiment. (see Table 1)

SPPS OPERATION 1981-1984

Operational Features	1981	1982	1983	1984
Beam (Gev)	273	273	273	315
$Beta_H$, (m)	2	1.5	1.3	1.0
$Beta_V$ (..)	1	0.75	0.65	0.5
Int. Luminosity (nb^{-1})- Average values				
i) per run		0.5	2.1	5.3
ii) per day		0.4	1.8	5.1
iii) per year	0.2	28	153	395
Luminosity ($10^{29} cm^{-2} s^{-1}$)				
i) peak		0.5	1.7	3.5
ii) average per run		0.1	0.5	1.0
A) Hours Scheduled	698	1750	2064	2136
B) Hours Realized	140	748	889	1065
Number of runs	14	56	72	77
Average run duration (h)	10	13	12	15
% of runs termin. by faults		41	40	32

The steady improvement in performance reflects a gradual mastering of a complex chain of accelerators. At least 3 days of stacking of antiprotons in the accumulator (AA) is required before making the first transfer to the SPS with an initial luminosity in excess of $10^{29}cm^{-2}s^{-1}$. Once the initial stack is established, an equilibrium situation is reached where approximately 30% of the stack is transferred to the SPS in 3 bunches. As long as the SPS can hold the beams for of the order of 20 hours the AA then has time to replenish the stack ready for the next transfer.

The transfer sequence is heavily dependent on software in order to make it as safe as possible. The nucleus is a high-level job manager called the "sequencer"[1]. This controls the complex sequence of operations needed to prepare the SPS and its transfer lines and to control the antiprotons injection process. It has the ability to abort the transfer up to the very last moment if a fault condition is detected. Such elaborate software control is more reminiscent of a rocket launch than an accelerator operation.

In the first three years of operation, the luminosity lifetime was of the order of 15 hours, limited mainly by the antiproton lifetime. This is well suited to the cadence of one antiproton transfer per day. If the coast is terminated manually the SPS is prepared for the next injection as quickly as possible. Generally 3-4 hours is necessary to follow fully all the procedures, retune the machine, checkout of the beam lines with protons, antiproton pilot pulses, etc. However, as will be shown later, at least one third of the coasts are terminated prematurely. In these cases it is often unattractive to prepare quickly for a new fill since time is needed for the accumulator to replenish the stack. Statistics on the mean time between fills may therefore be misleading.

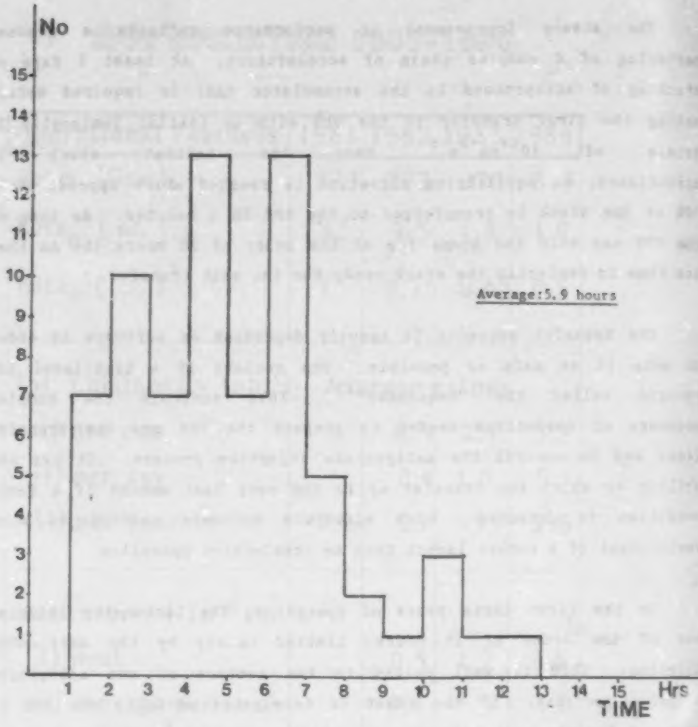

Fig. 1: Time taken in setting up for fill: 1984

3. COMMENTS ON THE DUTY FACTOR

There has been a gradual increase over the 4 years in the percentage of time during which the SPS had colliding beams such that experimental physics data could be taken compared to the total scheduled operating hours.

There are 4 other factors which take time

- (i) Setting up for coast
- (ii) Machine studies
- (iii) Access, mainly for the experiments
- (iv) Fault diagnosis and equipment repair.

The efficiency of the collider is judged by the experimental teams on the basis of total hours of colliding beam combined with the luminosity; that is to say what really counts is the integrated luminosity. The increase of the latter by a factor of 2.6 from 1983 to 1984 was more significant than the increase in duty factor from 43% to 50%.

In the early stages of an experiment there is little demand for peak luminosity performance and what is important is the total hours with collisions. This is also the case at the beginning of a new period of operation and there are demands for low luminosity calibration runs. The time requested for calibration and setting up runs in any year however is small, less than 10% of the total scheduled.

Figure 1 is a histogram of the numbers of hours taken for setting up in preparation for a fill for all coasts in the year 1984. The average time taken, of nearly 6 hours, reflects the dependence on the number of antiprotons available in the accumulator rather than any inefficiency in the preparation. The time between fills is particularly long following the loss of a stack due to a technical failure.

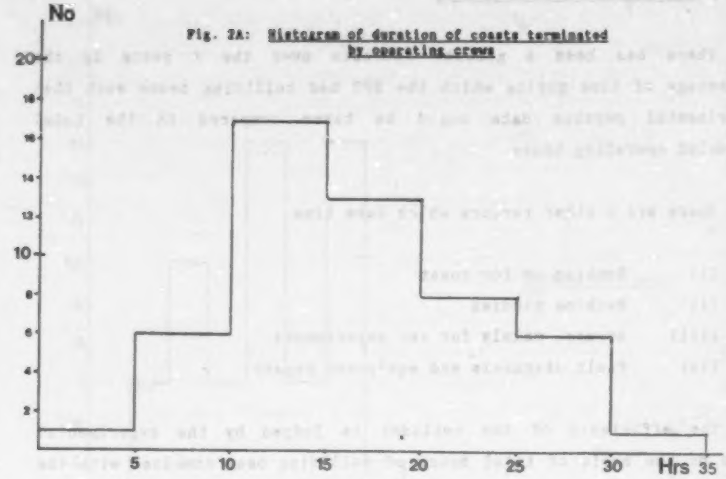

Fig. 2A: Histogram of duration of coasts terminated by operating crews

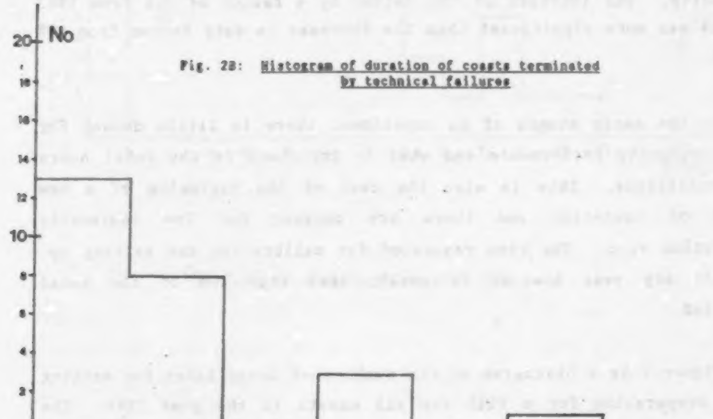

Fig. 2B: Histogram of duration of coasts terminated by technical failures

Access requests are grouped together and scheduled as much as possible in advance since full use has to be made of these relatively rare occasions. It is not unusual to have 30 people entering the UA1 zone for a 4-hour access period. Shorter accesses between fills are also catered for.

Access for accelerator repairs is combined with experimentalists' access. Much of the power supply testing and improvement was done during access to the experimental zones.

Machine studies require a variety of beam conditions. In addition to the studies on the end of a physics coast, time needs to be set aside for proton-only coasts and collisions with pilot (low intensity) antiprotons. Both these uses of scheduled time are necessary for the efficient operation and development of the accelerator and the experiments and so should not be considered negatively when viewing the duty factor statistic.

4. COMMENTS ON COAST DURATION

Of the 77 coasts in the 1984 run of 13 weeks, 25 were terminated prematurely due to technical failures. For the rest the average store duration was 17 hours. The distribution of coast length is given in Figure 2. The longest lasted over 31 hours and over the 4 years of collider operation the longest coast recorded was 42 hours.

Statistically, if the coast lasted longer than 7 hours, it would probably be 'killed' by the crew at the end of its useful life.

The luminosity lifetime for most of 1983 and 1984 was less than 20 hours, typically between 13 and 15 hours. The usefulness to physics of the coast (largely determined by background considerations) is ended after about one luminosity lifetime. Of course this judgment is dependent upon another fill being imminent. In the case of problems with the proton/antiproton sources the coast was kept longer hence the occasional exceptionally long coasts. At the end of the coast for physics run, Machine Studies would frequently be allocated another 2 hours; this time is not included in the statistics.

TABLE 2

ANALYSIS OF COASTS LOST DUE TO TECHNICAL FAILURES

	1982	1983	1984
Number of coasts	56	72	77
Coasts lost	23	28	25
Cooling-systems	–	1	4
Electricity System	5	2	3
Voltage Drops	9	10	3
Controls	6	2	–
Vacuum	–	–	1
Main Ring Power Supplies	2	3	3
Low Beta Supplies	–	4	2
Experimental Magnets	–	1	3
RF	1	1	3
Others	–	4	3

Access for minor repairs and modifications to detectors were usually scheduled for 2 to 4 hours on average 3 times per week.

There is a tendency to favour a 24-hour cycle of filling. Equipment that is used only during the transfer, injection and acceleration process can only be tested out of coast mode; it is more efficient to uncover problems during the normal working hours of the laboratory.

As the luminosity lifetime increased above 20 hours - to about 26 hours - and confidence in the equipment reliability improved, the 24-hour cycle was abandoned in favour of increased coast time and integrated luminosity.

5. TECHNICAL FAILURES (Fault Diagnosis and Equipment Repair)

In the two years 1983 and 1984, (after the starting years 1981,1982) the majority of the coasts lost owing to technical faults was caused by various, mostly minor and unrelated random failures. During the fixed target operation (53% of total scheduled time per year for physics) faults are analysed and repaired with the more stringent collider operation in mind.

Voltage dips on the mains supply (on an overhead line directly from a hydro-electric power source, Genissiat 50 km from CERN) contributed about 30% of the technical failures in the years 1982 and 1983. In the latter part of the 1983 run and for the 1984 period the system was desensitized to stand dips of up to 25% on either one of the 3 phases before the power supplies tripped off. The SPS never schedules collider operation during the summer months: evening thunderstorms after the hot summer days are common in July and August and have caused serious perturbations even for fixed target operation.

The demand for a higher operating energy of the collider resulted in the increase from 273 to 315 GeV coasting energy. For this among other modifications, booster water pumps had to be installed in all the sextants of the ring. The upgrade was very successful but there were two coasts lost in relation with this system. Often in such cases the diagnosis and effective elimination of the fault are hampered by human errors owing to the lack of familiarity with the new conditions. The balance between known steady operation and improved running conditions is the constant dilemma for Operations personnel.

Care must be taken that all magnets which produce fields seen by the primary beams are engineered to the same high standard as the accelerator components. Some coasts have been lost because detector magnets have failed to respond correctly to commands given (the correct balance between the magnet and its compensator magnets has sometimes not been observed).

6. COMMENTS ON BEAM QUALITY

The SPS has restrictions to its operation based on the availability of antiprotons. The required degree of reliability of its equipment must be higher and loss of stores is more serious than in the case of a proton proton collider.

What both type of machines have in common however is the need to provide stable beam collisions with low backgrounds over long periods of time. This we call the Beam Quality.

What is difficult to obtain from the statistics of accelerator operation is a measure of the quality of the operation as seen by the physics community and by the operations crews themselves.

It has become a "truism" that for good operation one needs good diagnostics. In the case of the collider, the measurement of beam parameters and confidence in the results is of paramount importance. In fact, the improvement in collider performance has been closely correlated with the development of improved diagnostics. The uncertainty caused by a doubtful measurement can polarise an investigation, preventing a logical diagnostic of the fault. In this group one includes orbit measurements, ν values, beam emittances, chromaticity. Without reliable measurements,

ms of high background for example cannot be traced to a movement in
osed orbit due to magnet drifts or separated out from a problem with
raping system.

One problem of high background was finally traced to a noisy linear
icmeter which controlled the position of a collimator block; once
fied the problem was quickly solved but many hours were spent
ing false ideas.

We have already stressed the need for reliable software when
g about the Sequencer.

What is important for operation in its search for improved beam
y is that the control system can accommodate an ever changing
on. New ideas, new sources of difficulty must be included in the
re so that the human element can be minimised. Once an operation
re is established it should never be overlooked and this logically
converting the procedure into software (not in the form of a written
tion that the operator/engineer can call up on his VDU!).

For good beam quality and diagnostics it is important to have good
anks not only of the equipment parameters but also of the beam
eristics. The facility of being able to study the evolution of a
er over a number of shots is very important and prevents the
ion of the thought process to one channel because a particular
ment looks strange.

ANALYSIS OF SPS COLLIDER OPERATION IN 1984

The SPS operated in collider mode from 20th September to 20th
r 1984, with a scheduled break of 48 hours for a technical stop at
of October for maintenance purposes in the SPS and the CPS (the
r complex).

There were only 10 days allocated between the end of Fixed Target
n and the start up of the Collider Period, during which both large
nts had to be installed.

As a result, the first week (168 hrs) was scheduled as start up (and is not included in the statistics below).

During each week access to the ring and experiments was usually scheduled for two periods of a few hours each. On average, half of this time was masked by access during the recovery time from technical failures.

	P	SU	MD	Tech. fail.	Access	Total
Total hours (13 weeks)	1065	484	184	209	25	1968
% of total	54.1	24.6	9.4	10.6	1.3	
Total operating hours (11 full weeks)*	948	444	179	209	25	1805
% of totals	52.5	24.6	9.9	11.6	1.4	
Average per week (hours)	88.5	41.5	16.7	19.5	2.4	

* 48 hours technical stop hence 10.7 weeks

Average number of fills per week 7 (6.8)

P = Physics,
SU = Setting up, preparation of filling,
MD = Machine studies,
Tech.fail. = Time lost due to failure of equipment,
Access = Time for access to experiments or accelerator.

8. CONCLUSIONS

As in any other hadron storage ring the operation of the SPS as a proton-antiproton collider imposes severe demands on equipment reliability. The scarcity of antiprotons excludes fast refilling after equipment failure and makes the impact of such faults on the overall productivity particularly dramatic.

The collider is particularly vulnerable to fluctuations in the primary services. The most important single perturbation outside the control of the SPS Division is due to voltage dips on the main 380 kV supply. This problem may be accentuated by the presence of long exposed overhead feeder lines to the laboratory and excludes colliding beam operation in periods of thunderstorm activity (most of the summer months).

The average time of 5.9 hours needed to refill the machine is mainly determined by the number of antiprotons available in the accumulator. Nevertheless, the achievement of the best possible beam quality, transfer efficiency, emittance, etc. requires a very careful, systematic setting-up for each fill, needing at least 2-3 hours.

References:

1) A Multi-processor, Multi-task Control Structure for the CERN SPS
(paper presented at the Eur. Conference - Berlin - September 1983)
SPS/AOP/Note 83-8
C. Saltmarsh

Appendix 7.1

QUENCH DETECTION AND PROTECTION

Introduction

The failure of the quench protection system during a quench in an accelerator composed of superconducting magnets can be dramatic. Even without the rupture of the cryostat, it takes on the order of one week to replace the damaged magnet. If the cryostat should rupture, there is the additional problem of massive contamination. For this reason, quench protection systems are designed to be ultra-reliable.

However, a reliable quench protection system does not guarantee that magnet replacements will be kept to a minimum. The quench protection system can only prevent the loss of a magnet due to ohmic heating whereas most magnets will probably be replaced due to nonquench-related pathologies such as vacuum leaks, faulty splices, electrical shorts, heat leaks, field quality problems, or failure to reach the designed field level. Although these failures are prone to occur mostly during commissioning, especially if only a fraction of the magnets is cold-tested prior to installation (see Appendix 6.10), faulty magnet design and inadequate quality control during magnet fabrication can plague the accelerator throughout its operating life and are probably more critical than the problem of quench protection.

A7.1.1 Separate sectors

Having made this point, let us first consider the problem of quench protection in general. The sheer size of the SSC makes it advantageous--at least during commissioning--to divide the task into more tractable chunks, i.e., 12 independent sections which are independently powered. This is especially the case if the first magnet cooldown and power test occurs in-situ, as some fraction will then be identified as faulty and replaced. Another advantage of independent sectors is that the power circuits do not overlap more than one refrigeration system. The requirement that all the refrigeration systems be functioning prior to any power tests is bound to make commissioning more difficult. And of course, smaller cirult lengths reduce the stored energy per circuit and reduce the local damage in case the circuit inadvertently opens. Finally, the longer the circuit, the longer the common communications link that synchronizes the response of the distributed power supplies and dumps after a quench.

A7.1.2 Magnet types

The question of one-in-one, versus dual, versus two-in-one magnets, is probably immaterial from the perspective of the quench protection system. A quench in a magnet which is coupled either cryogenically or magnetically will in general dump the beam in the adjacent aperture due to secondary quenches. This may impact on the refrigerator design or the SSC physics schedule if the retention of the second beam is considered an advantage (see Appendix 6.7). However, the quench detection system design is unaffected as it has to be designed to accommodate multiple quenches in any case.

The magnet characteristic that could drive the design of the quench protection system design sufficiently to impact commissioning and operation is the peak magnetic field. Using only the peak field for comparison, the contending magnets divide naturally into two categories: the iron dominated 3 T superferric design as opposed to the coil dominated 5 T (no iron) to 6.5 T (cold iron) designs. The superferric magnet operates at a current of 10 kA. Its cable reaches a temperature of 500 K after 44 MIIT's.* For comparison, the 6.5 T cold iron design operates at 5.4 kA and its cable reaches 500 K after 8.5 MIIT's. Note that in spite of their radically different designs, the time constants (assuming exponential current decay) to protect these magnets are quite similar, i.e., 0.88 s and 0.54 s for the 3 T and 6.5 T designs, respectively. However, the relatively low inductance (0.1 mH/m) of the superferric design allows longer magnet lengths to be protected by passive means.

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*The time integral of the square of the current during a quench, in MA^2s.

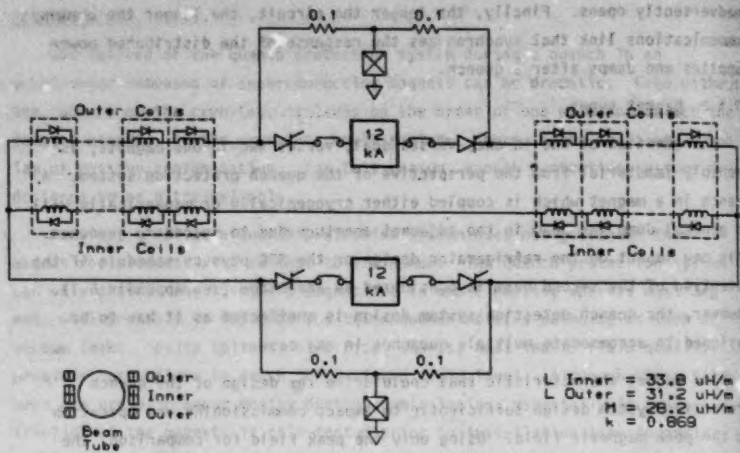
0.1
0.1
Outer Coils
Outer Coils
12 kA
Inner Coils
Inner Coils
12 kA
0.1
0.1
Outer
Inner
Outer
Beam Tube
L Inner = 33.8 uH/m
L Outer = 31.2 uH/m
M = 28.2 uH/m
k = 0.869

Fig. A7.1-1 Superferric dipole power and quench protection circuit.

A7.1.3 Superferric magnet design

The proposed power circuit and quench protection scheme for the superferric dipole magnets is shown in Fig. A7.1-1. The four inner dipole turns and four outer dipole turns are powered independently to allow cancellation of the sextupole. Additional separate high current busses (not shown) are required to power the distributed decapole windings in the dipole and the separate quadrupole magnets. The nominal half cell length is 160 m of which 140 m are occupied by a single dipole. Although a single unit, the coils of the dipole are wound in 35 m increments as shown in Fig. A7.1-2. Current is extracted from a quenching dipole via a pair of cold diodes (one for each inner and outer coil). The separate quadrupole magnets are each protected with a single cold diode. The details of the decapole winding protection are

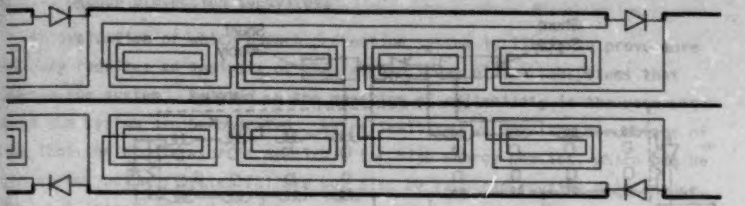

Fig. A7.1-2. 140 m dipole assembled from 35 m sections.

not yet certain, but presumably one cold diode per decapole winding will suffice. The energy from the nonquenched elements of the dipole circuit is extracted with two resistive dumps. The quadrupole and decapole circuits will also require at least one dump each. Quench detection is proposed to be done with analog comparators connected in a pyramid configuration as shown in Fig. A7.1-3. Four independent quench detection circuits of this type are required--one each for the inner dipole coil, outer dipole coil, quadrupole and decapole circuits.

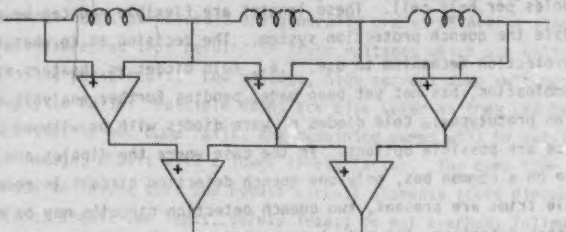

Fig. A7.1-3. Analog quench detection circuit.

A7.1.4 High field magnet designs

The proposed power circuit and quench protection scheme for the high field magnet group is shown in Fig. A7.1-4.

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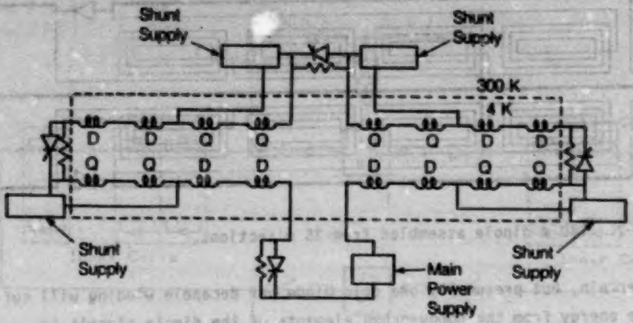

Fig. A7.1-4. High field magnet power and quench protection circuit.

The dipoles and quadrupoles are powered by a common bus. The cold iron designs may require current trims as shown to compensate for unequal iron saturation between the dipole and quadrupole magnets. The half cell length for all high field accelerator designs is presently 100 m. Design A (6.5 T at 5.4 kA) has five 16.6 m dipoles per half cell whereas Design B (5 T at 6 kA) has eight 12 m dipoles per half cell. These lengths are flexible and can be modified to accommodate the quench protection system. The decision as to what type of quench protection mechanism to use, i.e., cold diodes vs. heaters vs. some other combination, has not yet been made, pending further analysis and test results on prototypes. Cold diodes or warm diodes with or without heater assistance are possible options. In the case where the dipoles and quadrupoles are on a common bus, only one quench detection circuit is required. If quadrupole trims are present, two quench detection circuits may be required. After quench detection, the magnet current decays through four series-connected dumps. Persistent current related sextupole and decapole fields are a problem in coil-dominated magnets at injection unless the superconductor filament size is reduced to at least 5 microns. If required, the distributed sextupole and decapole trim coils will be low-current circuits and can be made to be self-protecting at their power supplies. A microprocessor-based quench detection system similar to the one in use at the Tevatron has been proposed.

A7.1.5 Quench protection subsystems

An evaluation of which quench protection system is likely to prove more reliable requires an analysis of the failure modes of the subsystems that compose the system. Related to the question of reliability is the ease with which the system can be operated. By reliability, we mean the percentage of time that the accelerator is available for high energy physics, which can be reduced not only by system failure but also by required routine maintenance, check-out procedures and operator errors. For convenience, the subsystems considered in this report consist of the dump subsystem, the current bypass subsystem and the quench detection subsystem. In the case of the superferric magnet, a cold diode protection scheme will be assumed. A preferred method may be to add safety leads so that the diode can be at room temperature. Both the cold diode and heater assisted options will be considered for Type B and Type D magnets, where a selection has not yet been made.

A7.1.6 Dump subsystem

This subsystem is discussed first because it is the easiest to understand. If a quench occurs somewhere in the circuit, the circuit power supply voltages are set to zero (bypass mode) and one or more resistive elements (dumps) are inserted into the circuit to reduce the decay time constant of the circuit current. Several dumps per circuit are generally preferred over a single dump of higher resistance, as this results in lower voltages which are uniformly distributed along the circuit. Low voltage, high current dump switches are relatively easy to build. Multiple dumps are also safer as they can be designed such that if one dump fails, the remaining dumps will be sufficient to assure no damage, albeit with a lower safety factor. The dump time constant is chosen to insure that the bypass circuit elements (cold diodes or warm thyristors, stabilized leads, safety leads) do not overheat following a quench. In the interest of economy, these elements are not sized to carry the circuit current continuously. The dumps also protect the helium cooled power leads in the event of inadequate cooling.

The superferric magnet design has four independent high power circuits although the inner/outer dipole circuit dumps have a common quench trigger.

The 0.2 ohm dump resistances of the dipole circuit seem high for a 10 kA circuit. This results in 1 kV to ground (2 kV with a short) which is an excessive voltage in a gaseous helium environment. A better solution would be to increase the number of dumps by a factor of two or, if the bypass system allows, to increase the dump time constant. Assuming a minimum of one dump each for the quadrupole and decapole circuits, the superferric design requires 4 dumps per sector per aperture. The high field magnet design has one high power circuit per sector per aperture, which contains four commonly triggered dump circuits. Synchronization of the dump firing to the order of 1 ms is necessary to reduce voltage-to-ground transients. The signal path linking the quench detection subsystem to the dump subsystem must have high integrity.

A7.1.7 Quench bypass subsystem

The purpose of the bypass subsystem—whether it is composed of cold diodes, warm diodes or thyristors—is to permit the circuit current to bypass a quenched magnet until the dump sybsystem has had sufficient time to reduce the circuit current to zero. All of the competing accelerator magnet designs can be protected passively, i.e., with a diode per coil if they do not contain thermally isolated (longitudinally and/or transversely) superconducting cable. For short magnet lengths, this assures rapid resistance growth which forces the magnet current into the shunting switch with a rate determined by the coil inductance and coil resistance. As the magnet length protected by a diode is increased, the coil inductance will increase linearly whereas the coil resistance is limited by the quench velocity. Therefore, the magnet length should be limited to that length which results in less than the maximum allowed cable temperature (500 K to 800 K maximum for NbTi cable with Kapton insulation). If it is considered an asset to have magnets which are longer than this length, additional diodes can be added (Fig. A7.1-5) which electrically reduces the coil lengths to acceptable fractions of the physical magnet length.

An alternative is to add heaters to the coil. This achieves linear resistance growth with coil length and allows any coil length to be protected with a single diode, subject only to the inductive voltage bias that results from the magnet current cycle. A heater power source consists of a charged capacitor that discharges into a heater through a thyristor. Eight hundred of

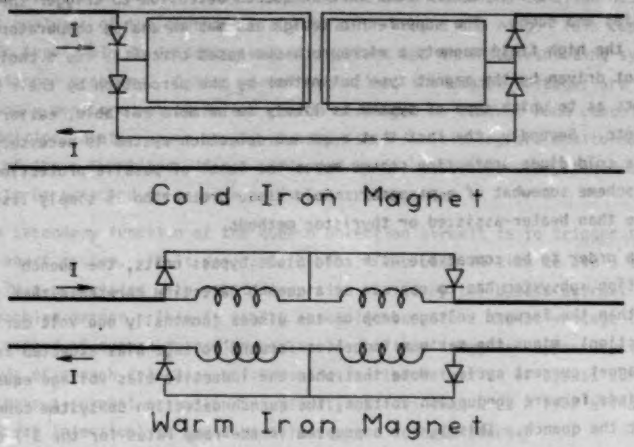

Fig. A7.1-5. Possible segmentation of magnet coils to allow more diodes for passive quench protection.

these supplies are used in the Tevatron quench protection system, and they have proven reliable. An even more reliable heater supply design is practical with a larger engineering investment. Heaters can be used to protect single magnets with cold diode bypasses or to protect a string of magnets--say a half cell--which has either a common cold diode, warm diode or warm thyristor bypass loop. Warm switches require safety leads, which have a nominal heat leak of 1 W/pair to 4 K. If thyristors are used, they should be operated as redundant pairs, each thyristor capable of carrying the full current in case one of them fails to trigger. Since they have separate gate drives, each thyristor can be checked for proper operation with a miniramp prior to each beam cycle. Safety leads and redundant warm bypass loops have the advantage of reducing the damage due to an open circuit in the magnet bus.

A7.1.8 Quench detection subsystem

All the magnets require some sort of quench detection to trigger the power supplies and dumps. The superferric design assumes an analog comparator circuit, the high field magnets a microprossesor based circuit. These choices are not driven by the magnet type but rather by the perception by their proponents as to which type of system is likely to be more reliable, easier to use, etc. Secondly, the fact that a quench detection system is necessary even with a cold diode protection scheme makes the label of passive protection for this scheme somewhat of a misnomer. Cold diode protection is simply less active than heater-assisted or thyristor methods.

In order to be compatible with cold diode bypass units, the quench detection subsystem has to operate at a quench detection threshold that is less than the forward voltage drop of the diodes (nominally one volt during conduction), minus the maximum inductive forward voltage bias expected from the magnet current cycle. Note that when the inductive bias voltage equals the diode forward conduction voltage, the quench detection subsystem cannot detect the quench. This is not a problem if the ramp rates for the 3 T and 5 T or greater systems are less or equal to 10 A/s and 5 A/s respectively and the quench detection level is approximately 0.5 V. The Tevatron's microprocessor based quench detection level is 0.5 V with a 60 Hz bandwidth. Noise background is typically 0.1 V. Additional filtering would be acceptable in the cold diode case. An advantage of a system not using heaters is that the quench detection system need not be active after the first quench has been detected as the dumps have now been actuated and subsequent quenches will bypass automatically. An advantage of the thyristor bypass combination is that the system can be designed to operate at a 10 V quench detection level as the thyristors are not shorted until the quench is detected.

A comparison of an analog detection method versus the digital microprocessor-based detection method normally neglects the control system functions that the digital system performs. The prime function of the digital system is to analyze voltage inputs in order to detect the presence of a quench. However, it also compensates for input offsets, monitors the helium cooled power leads and continuously monitors circuit voltage-to-ground to detect ground faults and power supply and dump malfunctions. A 10 s circular buffer keeps a permanent record of quench related functions to allow post-event analysis of the quench for any location around the ring. This capability is invaluable in detecting magnet problems and in troubleshooting system operational problems. During normal operation, the magnet voltages are continuously monitored at 60 Hz and can be displayed on control-room consoles. In addition, heater power supply and thyristor functioning are monitored. Many of these functions--if not performed by the detection subsystem--would have to be switched to an alternative control system.

A secondary function of the quench detection circuit is to trigger the beam-abort system. It is desirable to abort the beam in time to avoid the beam loss associated with orbit distortion caused by the bypass current around a quenching magnet. This is easily accomplished with a magnet-voltage comparator method of quench detection and assured with a triggered bypass system. Methods of quench detection which depends on the detection of bypass current must have a current detection sensitivity of less than 0.25 A (for a 140 m dipole at injection) to avoid beam loss prior to beam abort.

A7.1.9 Component summary

A perhaps superficial comparison of the proposed quench protection systems is obtained if we catalog the number of separate components required to protect the competing magnet designs in an SSC environment as is done in Table A7.1-1. For comparison, the component count of the Tevatron--whose circumference of 6 km represents a size comparable to an SSC sector--is also listed, as the Tevatron represents the one currently available source of reliability data for large arrays of superconducting magnets. As in the text, the components are divided into roughly three subsystems. The component count sums over one aperture of one sector, and follows the discussions of the text and the sector and magnet descriptions as reported in Appendix A of the SSC Reference Designs Study.

Table 7.1-1

Quench Protection Comparison
(one aperture, one sector = 1/24 SSC)

Item	Tevatron	3 T(Fe)	5 T	6.5 T(Fe)
Dump Subsystem				
Max current (kA)	4.4	10	6	5.4
No. of circuits	1	4(1)	1	1 + trims
No. of power supplies	12	4	1	1
No. of dumps	12	4	4	4
Time constant (sec)	12	2.5	30	20

Item	Tevatron	3 T(Fe)	5 T	6.5 T(Fe)	
Bypass Subsystem Passive Option					
Approx. no. of half cells	200	80	80	72	
Dipole length (m)	6.4	140	12	16.6	
No. of dipoles per half cell	4	1	8	5	
No of quadrupoles per half cell	1	1	1	1	
Cold diodes/sector/aperture	-	320(2)	1360(2)	792(2)	
Bypass Subsystem Active Option					
No. of heater p.s.	800	-	160(3)	288(3)	144(7)
Cold diodes/sector/aperture -or-	-	-	160(3)	144(4)	72(7)
Warm diodes/sector/aperture -or-	-	-	480(4)	288(4)	216(7,4)
Warm thyristors/sector/aperture	1600(5)	-	320(5)	288(5)	144(7,5)
Quench Detection Subsystem					
No. of detection subsystems	1	4	1	2(6)	1(7)
No. of voltage channels	200	320	160	144(6)	72(7)

(1) Inner dipole, outer dipole, quadrupole and decapole

(2) Assumes 2 diodes per dipole, one diode per quadrupole or decapole

(3) Assumes dipole heaters are connected in series and quad heaters individually. One supply quenches a full half cell of upper and lower coils. The listed number of heaters is twice the number needed in order to achieve redundancy.

(4) Three diodes in series are required at each multi-dipole bypass to achieve sufficient forward voltage hold-off during a ramp. One diode is needed for each separate quadrupole.

(5) The number of listed thyristors is twice the number needed in order to achieve redundancy.

(6) Because of the trim supplies, the quadrupoles are on a separate bus. Therefore, two detection circuits per half cell are required.

(7) Cold iron without trims with dipoles and quadrupoles interlaced on same bus.

A7.1.10 Conclusions

The goal of this exercise is to determine if the requirements of the quench protection systems postulated for the competing SSC magnet designs can bias the magnet selection process. Comparisons are to be made on the basis of commissioning and operating ease. With this goal in mind, we make the following statements:

- The dump subsystems protect all of the magnet designs with equal ease. The number of dumps is roughly equal. The voltage and current levels of the 3 T dipole dumps are higher, but this should not present an insurmountable problem.
- If it can be demonstrated that they can be made to work reliably, passive diode bypass circuits are preferable to the heater assisted option. This is true even for the high field magnet designs. The 3 T system has the option of using cold diodes or warm diodes with safety leads. The high-field systems require more safety leads which need to be distributed within a half cell. This mechanical complication and the additional heat leak probably means that cold diodes are the only passive option. If cold diodes are chosen, a rigorous R&D effort is needed to identify suitable diodes and to investigate their failure modes and rates as a function of thermal cycles (cryogenic and bypass current) and radiation damage. If junction wafers without cases are used, the possibility of junction contamination must also be investigated.
- Either an analog or a digital quench detection method can be used. The selection will be based on their respective reliability and usefulness rather than on the magnet type. For cold-diode protected magnets, alternative detection methods which might detect early current rise, such as current transformers or diode temperature should also be explored.
- The heater/warm diode or heater/warm thyristor methods are viable alternatives to the cold diode bypass method if the diodes should

prove not to be suitable. Only roughly three times as many components as are presently functioning in the Tevatron are sufficient to protect both complete apertures of the SSC.

Some justification for a preference of the cold diode method and a caveat are in order. Cold diodes offer the advantage of simplicity which reduces the requirement of operational check-out procedures. It may also allow a simpler detection circuit design, i.e., one that is less likely to cause false quench indications.

The required number of cold diodes--at least in the two high field magnet designs--requires that an individual diode be approximately 10 times as reliable as a heater power supply. This ignores the fact that in a collider after the initial training period, the quenches are likely to be localized to refrigerator- or beam loss- sensitive regions of the lattice. If true, this means that only a limited number of diodes will experience multiple quenches and that the number of quench related diode failures will be approximately independent of the total number of diodes needed to protect the total magnet lattice. However, the heater power supply failure rate is probably proportional to the total number in use.

The diodes are expected to fail in the shorted condition. Radiation exposure increases the forward diode resistance and makes it more likely that the diode will short permanently during a quench. If the diodes are mounted in the insulating vacuum or in a segregated 4 K region, replacements should take only one day.

Now the caveat: Calculations with the program TMAX indicate that all the magnets, if protected by cold diodes as described in Table A7.1-1, will reach peak conductor temperatures that range from 500 K to 1000 K. Given the uncertainty inherent in this type of calculation--primarily caused by a lack of adequate quench velocity and resistance-versus-time data for specific conductors--it is quite likely that the diode count quoted for all the magnets will have to be increased by a factor of two to achieve more reasonable peak temperatures. This fact does not in itself negate the previous arguments, although as the number of diodes increases, the heater option becomes increasingly competitive.

We are now in a position to make a qualified comparison of the relative ease of protecting the superferric and high field magnets against quench damage.

- If the cold diode failure rate is low and localized to specific locations in the magnet lattice, the high-field magnet quench protection system is likely to prove more reliable because of the smaller number of detection cells. By diode failure rate, it is assumed that only the diode fails in the shorted condition. The magnet presumably should not fail because an adequate number of diodes per coil has been used.
- If the number of failed diodes is proportional to the number required to protect the lattice and is comparable to the detection circuit failures, then the superferric system will be more reliable because of the lower total number of diodes in use.
- If cold diodes prove unsuitable, the 3 T system can switch to warm diode bypass circuits; the high field systems to heater assisted bypass circuits. The relative reliability is now uncertain, as a smaller number of detection cells with heaters must be compared with a larger number of presumably simpler detection cells without heaters.

Appendix 7.2

MAGNET POWER SUPPLIES

Introduction

From discussions with our colleagues in the design group and after listening to our CERN colleagues describe their operating experience with SppS collider, it is clear that the quadrupole and dipole magnet currents must track within a few parts in 10^5. Requiring that the betatron tune spread be < 0.002 during acceleration (to limit particle loss) and during colliding beam operation (to limit emittance growth) implies current regulation with $dI/I < 2 \times 10^{-5}$ for the SSC. At first sight this requirement seems to provide an interesting design challenge, because in the Reference Designs Study dipole and quadrupole current was provided by 12 separate power supplies coupled together by differential transductors. Assuming that the current errors are random, each power supply must then regulate to a factor of $12^{1/2} \sim 3.5$ better than the overall regulation requirement. One way to avoid these random errors would be to connect the entire ring in series with 12 equally spaced power supplies. All except one would operate in the voltage control mode, with the remaining one operating in the current regulation mode to close the current regulation loop. For the ramp rates specified in the Reference Designs Study, the total power supply voltage requirement is less than 1360 volts for Design A (and D) and 270 volts for Design C (in both cases plus power lead drops), which is easily satisfied.

Because of the 4 volt "on" voltage for cold diodes, substantially higher voltages at low output currents are required to test the integrity of a passive quench protection system. This could be provided either by the main supplies or by separate low-power higher-voltage supplies which are switched in only during quench protection system tests. A penalty of the single-loop solution is the requirement of at least 12 high-current active and fast switches (as in the Tevatron power supply system). These must act reliably during upset conditions to limit voltage to ground by isolating the faulty sector from the circuit. Commissioning would be more difficult because the entire magnet is in series.

A7.2-2

During a talk on overall performance of the SppS collider, Lyn Evans from CERN described the magnet power supply regulation requirements. Because of intrabeam scattering they must limit the tune spread contribution from the power supply system to less than 0.001, which implies an overall current regulation of better than 3×10^{-5}. The magnet power supply system uses separate power supplies for the vertically focusing quadrupoles, the horizontally focusing quadrupoles, and the dipoles. During normal operation, the SppS thus achieves regulation within a factor of two of that required for the SSC.

To limit the sextupole and decapole contributions to an acceptable level in the 3T magnet, the current excitation is separated into three circuits. Fig. A7.2-1 shows the coil placement for one bore in the 3T design. The eight-turn main coil is separated into two separate circuits (inner and outer) with roughly equal currents at 3T. The third circuit is a two-turn separate decapole correction winding which requires about one-third the main current. The currents in the two main sections along with the correction winding current necessary to achieve the required sextupole tolerance are shown in Fig. A7.2-2 as a function of the dipole field. Only the sum of the two currents from the two main power supplies (I_{inner}) has to be regulated to the level mentioned above, with the tolerance on the ratio being a part in a thousand. The decapole correction winding current must be regulated to one part in 10^4. The quadrupole magnets are on a separate power supply. They require 3 kA at the

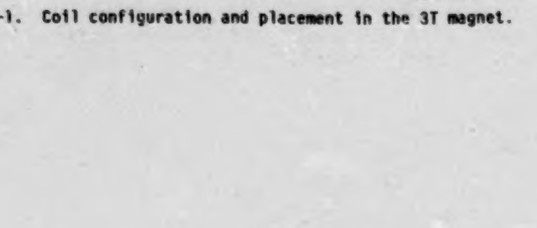

Fig. A7.2-1. Coil configuration and placement in the 3T magnet.

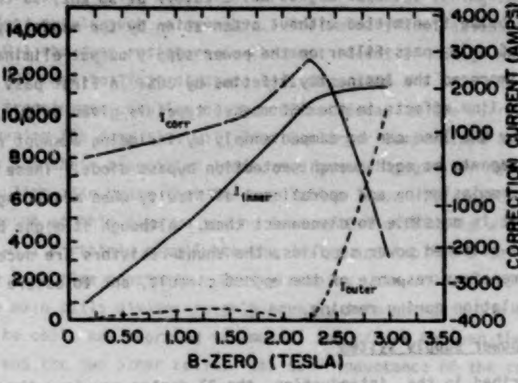

Fig. A7.2-2. I_{inner}, I_{outer} and I_{corr} vs. magnetic field for the 3T magnet.

peak collider energy, and their current must track the dipole sum current to a few parts in 10^5.

Since the dipole magnets are in series with the quadrupole magnets in the 6T design, tracking in a sector occurs automatically except for saturation effects in the dipoles. In Reference Design A this saturation effect amounted to less than ten percent at the peak field. With the iron further away in the new Design D, the saturation should only be a few percent. It is thus possible, by increasing the strength of the correction quadrupoles, to eliminate the high current shunt around the quadrupoles, along with its additional wiring and power supply complexity.

A feature of magnet power supply systems which has often been overlooked (with painful consequences) is the transmission-line behavior of the magnet inductance and the shunt capacitance of the coil to ground. The cutoff frequency of such lines can be in excess of several tens of kHz. One of the problems in commissioning the SppS collider was a dramatic sensitivity to switching noise spikes from the power supply. These caused field spikes at the milligauss level which drove the first betatron resonance at 12 kHz. As a transmission line, the SppS magnet has a cutoff at 50 kHz, so these noise spikes were being transmitted without attenuation by the magnet system. Installation of a low pass filter on the power supply output eliminated the spikes and improved the luminosity lifetime by 30%. A first pass analysis of transmission line effects in the SSC magnet types is given below. Propagation of signals by the line can be damped simply by including a shunt resistance across the magnets at each quench protection bypass diode. These resistors may pose a commissioning and operational difficulty when measuring coil leakage unless it is possible to disconnect them. Although it might be simpler to provide well-filtered power supplies, the shunt resistors are necessary to improve the transient response of the magnet circuit, and to assure the necessary current regulation during ramping.

A7.2.1 3T power supply system

As described in the introduction, the 3T design requires three separate high-current power supplies to assure an adequate field quality in the dipole magnets, as well as a separate high current power supply for the quadrupole magnets. Because the iron is not heavily saturated even at 3T, the three high-current circuits are tightly coupled. The self inductances per unit length of the inner (1), outer (2), and correction (3) coils are listed in Table A7.2-1 as a function of magnetic field.

Table A7.2-1

Coil inductances and coupling coefficients (3T)

Magnetic Field (Tesla)	Inner(1)	Outer(2)	Correction(3)
0.5	4.07	4.62	0.91
1.6	4.07	4.43	0.88
2.4	3.93	3.91	0.81
3.0	3.36	3.11	0.70

Coupling coefficients: K12 = 0.87 K13 = 0.813 K23 = 0.847

(Units are 10^{-5} Henrys/meter)

The tight coupling gives rise to a variety of effects during ramping and during transient events such as quenches. Preliminary indications are that the proposed 0.1 ohm dump resistors in the most recent 3T design must be reduced to 0.025 ohms to limit dI/dt to less than 3000 A s^{-1} in the outer coil, due to transformer coupling of the current decay in the correction coil. Lengthening the dump time will lead to larger temperature rises in the bypass diodes and their associated leads, and generally greater system stress. The tight coupling also means that the regulation loops will interact strongly, and, although at this time we see no fundamental difficulty with this coupling, it will certainly complicate the design and implies a delicate balancing of the loop time constants. During ramping, the voltage applied to either of the main coils divides roughly equally into charging the self inductance of the coil, and charging the mutual inductance between the coil being driven and the two other coils. The self inductance of the correction coil is small and its mutual inductance to the other coils is large. Combined with the larger dI/dt in the other coils, this results in requiring a four-quadrant power supply to provide the current. Figure A7.2-3 shows the current

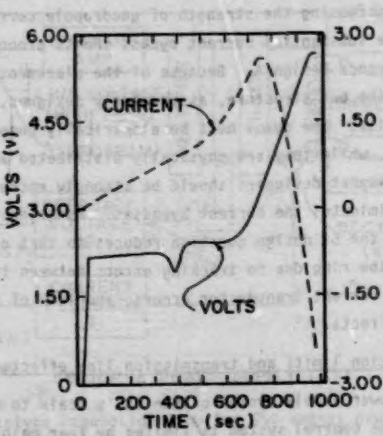

Fig. A7.2-3. Current and voltage for the 3T correction coil during ramping.

and voltage of the correction coil power supply, assuming a linear increase in the magnetic field during the ramp. A one-thousand second linear ramp is assumed. The circuit analysis program SPICE was used to calculate these data, as well as the current and voltage relationships during ramping for the other coils.

Clearly, a much more detailed analysis is required to make an accurate assessment of the likely performance of the 3T power supply system in view of the complexities disclosed by this brief study. It is certainly more complicated than the 6T supply system described in the next section.

A7.2.2 6T power supply system

The 6T magnet power supply system is simple in comparison to the one described above, since it consists of a single power supply per sector to provide the current for the series-connected dipoles and quadrupoles. As mentioned in the introduction, the present stainless-steel collared coil design for the 6T dipole magnet proposed for Design D probably places the iron far enough away from the coil to limit saturation effects to a few percent. Since the quadrupoles do not saturate, it may be possible to correct for the small dipole saturation by increasing the strength of quadrupole correction magnets, thereby eliminating the substantial current bypass shunts around the quadrupoles proposed in Reference Design A. Because of the placement of the quadrupoles in the lattice, the bus structure, as presently designed, to enable the current bypass is complex: The quads must be electrically connected at the ends of dipole strings, while they are physically distributed among the dipoles. The Design D magnet designers should be strongly encouraged to provide a design which eliminates the current bypasses. Assuming this simplification to be possible, the 6T design question reduces to that of overall current regulation of the ring due to tracking errors between the 12 sectors caused by differential current transductor errors, and lack of synchronism due to transmission line effects.

A7.2.3 Current regulation limits and transmission line effects

The ability of a power supply system of the SSC's scale to provide the current requested by the control system is limited by four main effects. The transducer that measures the current flowing in the magnet bus has both an absolute error and a transient response error in its conversion of current to voltage. The regulation loop has finite gain, built-in offsets, and limited bandwidth. Control systems provide digital numbers, which after conversion to analog voltages are used as the inputs to error amplifiers in the regulation loops. Each compares the voltage representing the current in the magnet to the command value, and this conversion has a finite error. Finally, because of the scale of the SSC magnet structure, transmission line effects set a lower limit on the current tracking error in a sector during ramping. Because of the large inductance of the 6T magnet, this transmission line effect sets a lower limit of $dI/I > 1 \times 10^{-5}$. With the 3T design, the limit is roughly one half this value. In addition to the above effects, the 3T design has errors induced through transformer coupling, which may in fact set the higher limit on the minimum current error. The analysis of this feature is just beginning, and will be a major part of the work carried out by this group during the next several weeks. The basic regulation loop being analyzed is illustrated in Fig. A7.2-4.

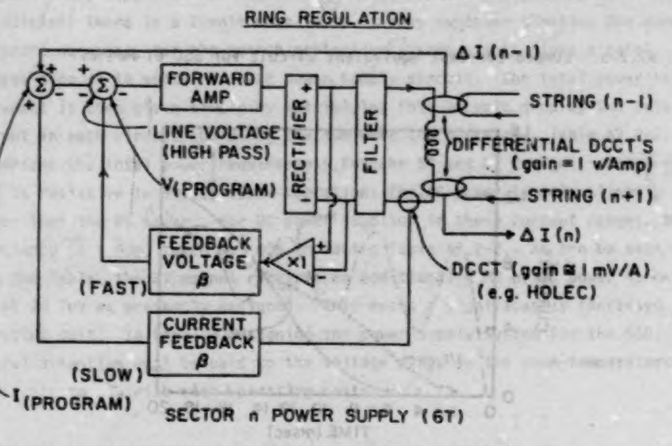
RING REGULATION
Δ I (n−1)
Σ
Σ
FORWARD AMP
RECTIFIER
FILTER
STRING (n−1)
LINE VOLTAGE (HIGH PASS)
DIFFERENTIAL DCCT'S (gain = 1 v/Amp)
V(PROGRAM)
STRING (n+1)
Δ I (n)
FEEDBACK VOLTAGE β
×1
DCCT (gain ≅ 1 mV/A) (e.g. HOLEC)
(FAST)
CURRENT FEEDBACK β
(SLOW)
I(PROGRAM)
SECTOR n POWER SUPPLY (6T)

Fig. A7.2-4. Prototype regulation loop for SSC magnet power supply.

To analyze the transient response of the magnet system, the circuit analysis program SPICE has been used with input parameters of inductance and capacitance to ground as measured on the 8-meter prototype 3T magnet, and with measurements of inductance and scaled estimates of capacitance to ground for the 6T magnet. Figure A7.2-5 shows a typical equivalent circuit representing the magnet. That transmission line effects are important is dramatically illustrated in Fig. A7.2-6, which shows the magnet response to a voltage step at the power supply as a function of distance from the power supply.

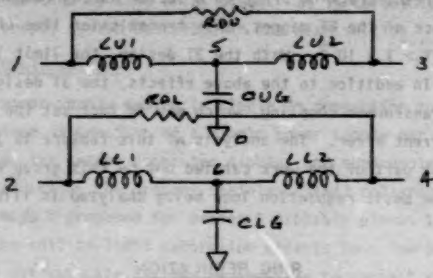

Fig. A7.2-5. Lumped constant equivalent circuit for SSC 6T Magnet.

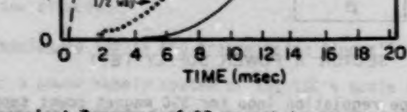

Fig. A7.2-6. Transient Response of 6T magnet to power supply voltage step.

With these features, what are the likely performance levels of the two different magnet power supply systems? The preliminary indications are that sensing the currents and providing the digital to analog command voltages are straightforward at the 10^{-5} level in each sector. Using high gain differential transductors and taking proper account of the delay line characteristics of the magnet, it appears feasible to link the individual power supply loops around the ring to achieve the required overall part in 10^5 average tracking tolerance for the 6T design. Further detailed analysis is required before the same statement can be made about the coupled 3T design. This analysis is presently under way, and, as mentioned above, a separate technical report will be issued in the near future.

As with any superconducting magnet system, the power dissipation in the magnet power supply system for the SSC occurs entirely in the room-temperature components during steady state operation. This power dissipation is dominated by the voltage drop in the necessary series filter inductance, and is typically 10 volts for a 150 microHenry 12 kA inductor. A well-designed lead system from the power supply to the magnet will have a total voltage drop of 2 volts. In addition, there is a 2-volt drop in the series switches shunting the dump resistors necessary for the quench protection system. This gives a total voltage drop of 14 volts for each power supply circuit. The total power requirement is then given simply by multiplying this 14 volt drop by the total current in each circuit and doing the sum over the circuits. Table A7.2-2 summarizes the total power requirements for the 3T and 6T designs. Since the load is resistive in steady state operation, the AC power is only slightly larger than the DC power. For DC power supplies in these current ranges, the efficiency is > 90%, taken as 100% in making Table A7.2-2. As can be seen from the Table, the 3T magnet requires an additional 4 MW of DC power to operate at 20 TeV as presently designed. This means a significantly increased operating cost. In finally designing the power supply system for the SSC, careful attention must be paid to the voltage drops in the room-temperature components to minimize such operating costs.

Table A7.2-2

AC power requirements for 3T and 6T power supplies.

Magnet	Current (kA)		DC Power (MW)
6T	I(dipole + quad) = 5.6		1.88
3T	I(inner) = 11.0	12.0*	4.03
	I(outer) = 10.0		
	I(corr.) = 2.5		0.84
	I(quad) = 3.0		1.01
		Total	5.88

*The circuits are configured so that only one of the power supplies provides the net current at full field.

A7.2.5 Conclusions

The power supply system for the 3T design is more complex because of the two high-current and two moderate-current circuits necessary to provide the required guide-field quality. Transformer coupling of these circuits complicates the regulation loop design and dictates using smaller dump resistors to limit dI/dt during a quench in order to prevent secondary quenches in the coupled circuits. The smaller dump resistors imply a larger temperature rise in the current bypass components, and a generally higher system stress. A four-quadrant 3 kA-output power supply presents a difficult design task, and has potential reliability problems as compared to a conventional DC supply. The operating cost of the 3T power-supply system is significantly higher than the 6T system. Because of the simplicity of the single-circuit design, combined with its lower operating current, the 6T design is preferred from an operational and commissioning point of view.

Appendix 7.3

VACUUM SYSTEM

The obvious differences between the 3T and the 6T magnet design vacuum system are the length of the physical system and the cross section of the beam tube. The 3T design has a beam tube with an elliptical cross section with a height of 2.42 cm and a width of 3.48 cm, while the 6T design has a circular cross section with inner diameter of 3.30 cm. In addition, the distance between pump down ports is 140 meters for the 3T design, while it is 100 meters for the 6T design (assuming that the pump-down ports are located only at the correction element packages). The principal difference is in the likely operating base pressure due to the different gas desorption rates driven by the synchrotron radiation power levels in the two designs. The relevant scaling relationships for fixed beam current are

$$\text{Synchrotron radiated power/meter} = \text{const.} \times B^2 \times E^2$$

$$\text{Number of radiated photons/meter/sec.} = \text{const.} \times B \;.$$

The critical energy, $U_c = 3hc\gamma^3/4\pi\rho$, (conventional definition = 1/2 of Jackson's definition) for the 3T design is 129 eV, and for the 6T design 258 eV. Since these energies are large compared to the typical binding energies (~1 eV) of adsorbed gas molecules to metal surfaces, it is probably the photon number flux that will determine the operating pressure. The base pressure will only depend on the number of protons per bunch and the bunch spacing since the circulation time around the machine (330 μs or 660 μs for the 6T or 3T design respectively) is long compared to the transit time for a molecule with greater than 0.001 eV kinetic energy. A 0.001 eV kinetic energy H_2O molecule has a velocity of 1.03×10^4 cm/s. The thermal energy of a molecule at 4.2°K is approximately 0.0003 eV, so its velocity is about 5.7×10^3 cm/s.

A7.3.1 Beam tube pumpdown time (commissioning)

The pumpdown time during commissioning and after a magnet replacement is determined solely by the outgassing rate of the inner surface of the beam tube and the pumping speed of the beam tube. Assuming no leaks, the base pressure achieved during this room-temperature pumpdown determines the total adsorbed gas inventory and will thus determine the operating pressure during colliding beam operation, when the beam tube is at 4.2°K. The steady state solution for the pressure in a pipe being pumped from one end and closed at the other, with a distributed gas load due to outgassing, is straightforward and given in Appendix 7.3. The pressure along the pipe is given by

$$P_x - P_o = QB[(x/C) - x^2/(2CL)]$$

where P_o is the pressure at the pump end of the pipe ($x = 0$) and P_x is the pressure at the point x, Q is the outgassing rate of the surface (in Torr-liters $s^{-1}cm^{-2}$), B is the cross section perimeter, and C is the conductance (liters/s) of the pipe. The maximum pressure is at the closed end of the pipe with a value given by

$$P_L = QBL/(2C)$$

where the pump pressure has been neglected. Q is of course a function of the surface treatment and the material and has a time dependence which can be represented after some short initial time t_o (typically 1 h) by

$$Q = Q_o\ (t_o/t)^{\alpha}$$

where Q_o is the outgassing rate at t_o and $\alpha = 1$ for most metals.[2] For a circular pipe of length L (cm) with a diameter d (cm), the conductance (liters/sec) is given by

$$C = 12.1\ d^3/L$$

for air at 20°C. For an elliptical cross section with semi-axes a and b, the conductance for a pipe of length L is

$$C = 137\ a^2b^2/[(a^2 + b^2)^{1/2}L]$$

for air at 20°C. Table A7.3-1 summarizes the maximum pressure for the 3T and 6T designs after 24 hours of pumping assuming $Q_o = 3 \times 10^{-9}$ Torr-liters s^{-1} cm^{-2} (mostly H_2O), which is characteristic of clean degreased stainless steel or copper. The average pressure along the beam tube is 2/3 of the maximum pressure, or 6.7×10^{-5} Torr for the 3T design and 2.4×10^{-5} Torr for the 6T design. These average pressures in the beam tube correspond to 1.4×10^{-3} monolayers and 5.8×10^{-4} monolayers respectively for the two designs. The

Table A7.3-1

Maximum beam tube pressure (24 hr.).

Magnet	Beam Tube Radius (cm)	Pump Separation (m)	Conductance (liters/sec)	P_{max}(Torr)
3T	1.21 x 1.75	140	0.041	10.0×10^{-5}
6T	1.65	100	0.087	3.7×10^{-5}

major gas load of the system, however, even with these relatively high pressures, is in the remaining adsorbed gas still bound with varying binding energies to the surface, typically representing several monolayers.

A7.3.2 Operating pressure

The actual operating pressure of the storage ring cannot be predicted accurately at this time. The above analysis indicates a substantial gas inventory before cryopumping begins, because of the poor conductance of the small beam tube and large separation of the vac-ion pumps. The equilibrium pressure in the beam tube during operation will depend on the power level of the synchrotron radiation and on the number of photons hitting the wall of the beam tube per second. The desorption process is not fully understood but is thought to proceed by the incident photon first ionizing one of the surface gas atoms and the resulting energetic electron transferring its kinetic energy (by dE/dx) to other surface molecules. These are left in an excited state whose electronic configuration is such that they are no longer bound to the surface and they leave. The literature on total desorption rates due to photons in the 1 to 250 eV energy in room temperature vacuum systems is not large, and is ambigious as to the initial conditions of the surfaces studied. For this reason, and because of the crucial importance of the beam tube vacuum, an extensive set of experiments are to be carried out over the next several months at the Brookhaven National Synchrotron Light Source to measure the desorption rate from cryogenic surfaces identical to those planned for the beam tube. From these measurements a reliable estimate of the beam tube operating pressure will be made.

The literature on desorption rates at cryogenic temperatures[3] points out one potentially troublesome mechanism by which H_2O is converted to H_2. Cryopumping is then difficult, since the vapor pressure of H_2 is 10^{-6} Torr at 4.2°K. The yield of H^+ ions from a surface with adsorbed H_2O illuminated by photons is shown in Fig. A7.3-1. As can be seen from the figure, H^+ ion yields of order 10^{-8} combined with photon fluxes of order 10^{15} per sec per meter will lead to substantial ion currents. These ions will become neutral, giving atomic H which may eventually combine to give H_2, leading to increased operating pressure. Although H_2O is the dominant molecular species, any molecule containing hydrogen will give rise to the same chain. Because of this sequence, the Brookhaven experiments should include runs with sufficiently low pumping speed to allow this potential buildup of H, and attempts should be made to measure the H_2 partial pressure.

Because of the smaller magnetic field, and hence a smaller number of UV photons striking the beam tube surface, the 3T design probably has a slight edge in terms of lower operating pressure. This will only be true if there is additional distributed pumping speed installed to lower the warm beam-tube pressure. It may be necessary for both the 3T design and the 6T design to install substantial warm distributed pumping, to lower the gas inventory to a low level before cryogenic operation. Sp̄pS experience indicates that the beam lifetime is substantially shortened if the pressure exceeds 10^{-9} Torr, setting the scale for the quality of the beam tube vacuum for the SSC.

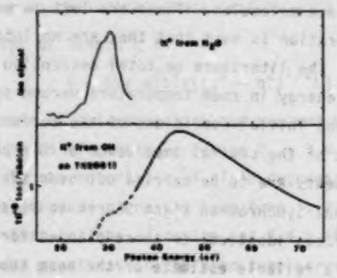

Fig. A7.3-1. Comparison of H^+ ion yield as a function of photon energy (Ref. 3).

A7.3.3 References

1. A. Roth, Vacuum Technology, 2nd Edition, pg. 131, North Holland (1982).
2. Y. E. Strausser, Proc. of the Fourth Vacuum Congress 1968, pg. 469 (1968); V. S. Zhilnin, et al., Proc. of the Fourth Vacuum Congress 1968, pg. 801 (1968).
3. T. E. Madey, et al., Desorption Induced by Electronic Transistions DIET I, pg. 120, Edited by N. Tolk, et al., Springer-Verlag (1983).

Appendix 7.4
MAGNETIC CORRECTION ELEMENTS

The SSC dipole magnets contain excessive higher magnetic multipole moments. These multipoles are the result of conductor placement errors, iron saturation, and persistent currents in the superconducting filaments of the conductor. A lack of up-down or left-right symmetry can also result in unwanted magnetic moments. Such asymmetries are present to varying degree in the two-in-one and dual magnet designs.

The 3 T superferric magnet field errors are dominated by iron saturation and, to a lesser extent, by conductor placement. The recent addition of turns near the pole tips to cancel the decapole means that persistent currents may also have an effect. Finally, there is the small effect due to vertical magnetic coupling caused by vertically stacking both magnets in the same cryostat.

The high field magnet designs have errors that are dominated at injection fields by persistent currents and at high field by conductor placement errors. The one exception to this statement is the 6.5 T (Design A) magnet which has two apertures in a single iron yoke, with the magnet coils close to the iron. This magnet has additional magnetic moments due to the lack of left-right symmetry and a large sextupole moment at high field due to iron saturation. A later one-in-one design variation which uses nonmagnetic collars with a larger coil-iron separation (Type D) does not have magnet moments from these sources.

To limit the sextupole contribution to an acceptable level in the 3T magnet, the eight-turn main coil is separated into two separate circuits (inner and outer), and a single-turn separate correction winding requiring about one third the main current has been added. The currents in the two sections along with the sextupole correction winding current necessary to achieve the required sextupole tolerance are shown in Fig. A7.4-1 as a function of the dipole field. Only the sum of the two currents from the two power supplies (I_{inner}) has to be regulated to the level mentioned above, with the tolerance on the ratio being at the part in a thousand level. The correction winding current must be regulated to a part in 10^4. The quadrupole magnets are on a separate power supply and require 3 kA at the peak collider energy.

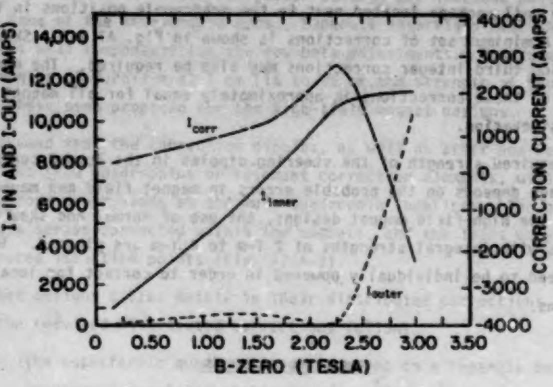

Fig. A7.4-1. I_{inner} and I_{outer} and I_{corr} vs. magnetic field for the 3 T magnet.

One proposal in the case of the high field magnets is cancellation of the persistent current-related sextupole moment with low-current sextupole windings which are wound on the outer radius of every dipole bore tube. The sextupole windings for a whole sector would be connected in series to one low current power supply (SDA), and would require regulation of the order of 0.1% at injection. The persistent current variation with temperature is expected to be of the order 1%. Therefore, the magnet temperature has to be measured with a reproducibility of 0.01°K to allow for compensation of this effect.

The distributed sextupole regulation tolerance for the high field magnets has been calculated assuming a superconducting filament size of 20 microns. If the filament size can be reduced without appreciably reducing the cable short-sample limit, and/or if passive superconducting turns are used to reduce the sextupole moment, the regulation tolerance of the distributed sextupole winding becomes less important, and at some point the windings may not even be necessary.

In addition to the corrections made within the dipoles, all of the SSC magnet designs require lumped corrections which can be combined into a correction coil package located next to the quadrupole positions in the magnet lattice. A minimum set of corrections is shown in Fig. A7.4-2. Skew, half-integer, and third-integer corrections may also be required. The number and strengths of these corrections is approximately equal for all magnet designs under consideration.

The required strength of the steering dipoles in the lumped correction coil package depends on the probable errors in magnet field and magnet alignment. For the high-field magnet designs, the use of normal and skew dipole correctors with integral strengths of 2 T-m to 4 T-m are planned. These dipoles need to be individually powered in order to correct for local orbit distortions.

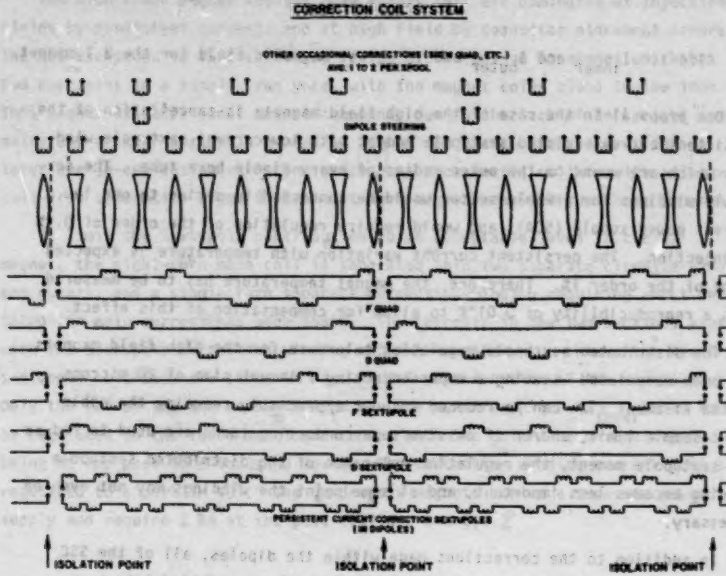
CORRECTION COIL SYSTEM
OTHER OCCASIONAL CORRECTIONS (SKEW QUAD, ETC.)
AVG. 1 TO 2 PER SPOOL
DIPOLE STEERING
F QUAD
D QUAD
F SEXTUPOLE
D SEXTUPOLE
PERSISTENT CURRENT CORRECTION SEXTUPOLES
(IN DIPOLES)
ISOLATION POINT
ISOLATION POINT
ISOLATION POINT

Fig. A7.4-2. SSC minimum correction coil system.

The quadrupoles in the lumped correction package are intended only to correct the tune of the accelerator arcs. Separate insertions near the interaction regions will compensate for the low-beta adjustments. Quadrupole correction strengths of 0.25 T-m at 1 cm (1% to 2% of the strength of the main quadrupoles) have been proposed for the high-field magnet designs.

It is assumed that the correction dipoles, as well as other non-repetitive correctors like skew quadrupoles or resonant correction elements, will have local low-current power leads at the main quadrupole locations. The other correctors are series-connected within the magnets, and the leads only surface at widely spaced isolation points (Fig. A7.4-2).

The magnet designs differ mainly in their distributed corrections. A summary of the required distributed corrections follows:

Quadrupole - The superferric quadrupoles are powered on a separate bus which requires a regulation tolerance of 0.001%.
- The 5 T no-iron magnet is on the same bus as the dipoles and automatically tracks the bend field.
- The 6.5 T (Fe) quadrupoles require on the order of 10% correction currents, which need to be regulated to within 0.01%.
- All of the magnet designs require comparable QF, QD coils for off-diagonal tune adjustments.

Sextupole - The superferric dipoles control the normal sextupole moment with independently powered inner and outer coils. The relative inner-to-outer coil current regulation of these 10 kA buses has to be better than 0.1%.
- For the coil dominated magnets it is proposed to remove the sextupole moment with low current (< 200 A) sextupole coils and/or smaller filaments and/or passive superconductor. In the worst case the regulation tolerance has to be better than 0.1%.
- All the magnets require lumped chromaticity correctors.

Decapole - The superferric dipole magnet has additional turns to reduce the decapole moment.
- If necessary, decapole correction coils can be added to the high field magnets .

(1) SSC Magnetic Field Quality Considerations - Summarized by H. E. Fisk

Appendix 7.5

RF SYSTEM AND BEAM STABILIZATION

The RF system provides the accelerating voltage to increase the beam energy from 1 TeV at injection to the operating energy of 20 TeV. It also stabilizes some collective instabilities while limiting particle loss due to intra-beam scattering and due to diffusion caused by RF noise. Stabilizing the collective modes and limiting the effect of intra-beam scattering specifies a lower limit to the momentum spread, while limiting the effects of RF noise requires a minimum bucket-to-bunch area ratio and spectral purity of the master oscillator. An accelerating voltage of 20 MV at a frequency of 356 MHz was selected in the Reference Designs, giving a ramp time of 1000 seconds and providing a sufficient bucket-to-bunch area ratio (3.2) to stabilize the transverse mode-coupling instability, which is driven by the broadband transverse impedance of the collider. To provide a longitudinal emittance growth time of at least 60 hours, it will be necessary to increase the momentum spread of the beam at 20 TeV by controlled noise injection. From experience with the S$\bar{p}$pS with RF noise limiting its early luminosity, and the subsequent success of a carefully designed feedback system suppressing this problem, the above choice of RF parameters for the SSC should avoid repeating the S$\bar{p}$pS experience. Avoiding trouble from noise will require a much more detailed analysis than has been performed to date but, there seem to be no fundamental problems.

Both longitudinal and transverse feedback systems will be required in the SSC to stabilize the beams against unwanted emittance growth. The longitudinal feedback system must have a system bandwidth such that it can correct dipole mode energy errors on a bunch-by-bunch basis, which is one-half of the bunch repetition rate, or 15 MHz. The solution chosen for Reference Design A (6.5T) was a 1 m long cavity with an average power level of 121 kW operating at 522 MHz. The cavity must of course be heavily overcoupled to provide the system bandwidth.

The transverse feedback system controls the coherent horizontal and vertical betatron oscillations. It is a much lower power system, at least for the 6T case. It requires a bandwidth of 15 MHz and the maximum power level of about 30 kW to damp injection errors. About 1 kW is required to damp the transverse rigid bunch oscillations driven by the machine impedance.

A7.5.1 Comparison of 3T and 6T RF systems

As discussed in Section 5, the only significant difference between RF systems in the 6T and 3T machines is at injection, where control of the transverse mode-coupling instability requires a minimum energy spread σ_γ, which is proportional to the transverse impedance Z_T and the ratio of the average amplitude function, β, and the slippage factor η. β/η scales as the tune times the machine circumference C. The required voltage is proportional to $\sigma_\gamma^2/f_0\gamma_t^2$. Since the beam frequency f_0 is inversely proportional to the machine circumference, and γ_t is proportional to the tune, the required voltage at injection goes as Z_T^2C.

The longitudinal and transverse beam tube impedances scale as

$$Z_L/n \sim C^{1/2}\ b^{-1}, \quad \text{and} \quad Z_T \sim C^{3/2}\ b^{-3}$$

where b is the radius of the beam tube. The RF system for the 3T design is about four times as long, and hence its parasitic impedances are four times as large. Since the betatron tune of the 3T machine is approximately $\sqrt{2}$ times the tune of the 6T machine, there are 1.4 times as many beam position monitor electrodes, etc., which implies 1.4 times the impedance from these sources. Table A7.5-1 summarizes the comparison between the two magnet styles.

To find the contribution of discontinuities for the 3T design, the contribution of the discontinuities of the 6T design was scaled both by the beam tube size ($(b_3/b_6)^{-3} = 2.42$) and the tune. The number of discontinuities is given by the tune and their size scales with the beam tube size. The omitted contributions represented by the contingency entry are assumed to be the same for both designs.

Using the above Table, we see that Z_T^2C is close to 8. For the 6T machine, the required energy spread σ_γ is 0.15 at injection. An RF voltage of 10 MV is then required. Scaling by Z_T^2C, we obtain 80 MV for the required injection RF voltage of the 3T machine.

Table A7.5-1

Comparison of 3T and 6T machine impedances.

Component	6T		3T	
	Z_ℓ	Z_T	Z_ℓ	Z_T
Cold Cu beam tube	0.01	1.5	0.02	7.7
Warm Cu beam tube	<0.01	1.0	<0.01	1.0
Beam pickups	0.06	8.0	0.11	27.0
Kickers	0.02	8.0	0.02	8.0
RF Cavities	0.02	2.0	0.04	8.0
Discontinuities	0.05	7.0	0.09	23.6
Contingency	0.17	27.5	0.17	27.5
Total	0.34	55.0	0.45	101.8

(Units are ohms for Z_ℓ and Megohms/meter for Z_T. Only the broadband averages are listed in the table.)

Both machines require 20 MV during full-energy operation, and, with the provision for 20 MV in the 6T machine and 80 MV in the 3T machine, both can accelerate beams in 1000 seconds.

The main difference is the extra RF power capacity required for the larger ring. For the 20 MV design for the smaller ring in the RDS, 1 MW is required at the cavity, and nearly 2 MW at the klystron output. With 65% klystron efficiency and 100% efficiency between the AC transmission lines and the DC klystron input, we require 3 MW at the plug per ring, or 6 MW for both rings.

To obtain 80 MV at injection, the 3T design requires four times the number of cavities, and will require 24 MW during injection. Since injection conditions will obtain perhaps 10% of the time, 2.4 MW must be added to the total. On the other hand, during colliding beam conditions each 20 MV unit is operating at 1/4 of this voltage, and so a total of $4(1/4)^2 = 1/4$ as much power is dissipated in the cavities as in the 6T case. Unfortunately, klystrons yield maximum efficiency only when yielding full power. The efficiency vs. power curve for a typical klystron is shown in Fig. A7.5-1; at 25% of full power it operates only with about 25% efficiency. Under colliding beam conditions we thus expect the 3T ring to require 6 MW x (1/4) x (0.65/0.25) = 3.9 MW. The average RF power requirement for the 3T ring is thus about 6.3 MW. Since some savings are possible (e.g. by letting the beam drive two idling units while driving the others at high power), we conclude that the RF power needs of the two rings are nearly identical.

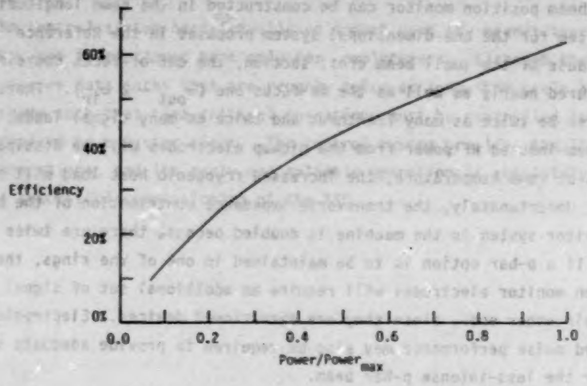

Fig. A7.5-1. Power efficiency of the 500 kW, 500 MHz Valvo klystrons used at CESR.

It is not the business of this report to comment on capital costs, but we nevertheless note that the RF system for the 3T ring is about four times as expensive as in the 6T case.

A7.5.2 Comparison of 3T and 6T feedback system requirements

From the Table, the impedances of the 3T machine are higher, and the same beam lifetime requirement for both designs implies that the longitudinal feedback system for the 3T design will require approximately twice the power of the 6T design. The transverse feedback system will require a similar increase in power for the 3T design compared to the 6T design. In any case these are small systems (of order 100 kW), and hence have minimal impact on the capital and operational costs of the machine.

Appendix 7.6

BEAM POSITION AND LOSS MONITORS AND CONTROLS

A7.6.1 Beam position and loss monitors

By extrapolating the operational experience with the Tevatron beam position monitor system to the smaller beam tube diameter of the SSC, and by assuming the improved noise performance of present day electronics, one expects that a two-dimensional beam position monitor can be constructed in the same longitudinal space allocated for the one-dimensional system proposed in the Reference Design. Because of the small beam cross section, the out-of-focus coordinate will be measured nearly as well as the in-focus one ($\sigma_{out} \sim 2\ \sigma_{in}$). There will of course be twice as many feedthrus and twice as many signal leads, but since the beam-induced RF power from the pickup electrodes will be dissipated in resistors at room temperature, the increased cryogenic heat load will be negligible. Unfortunately, the transverse impedance contribution of the beam position monitor system to the machine is doubled because there are twice as many ends. If a p-bar option is to be maintained in one of the rings, the beam position monitor electrodes will require an additional set of signal leads on their other ends, since they are directional devices. Electronics with improved noise performance may also be required to provide adequate sensitivity for the less-intense p-bar beam.

The impact of the beam-postion monitor system on the magnet selection process is minimal. The 3T design will require 1.4 times as many monitors, since its betatron tune is 1.4 times the betatron tune of the 6T design. There are proportional capital and operational costs, but the total system cost is small and hence has little impact. It would be an operational disaster if the final design of the beam position monitors did not have an adequate alignment method to locate them accurately with respect to adjacent quadrupoles. At the moment there is insufficient design detail to access with any accuracy whether the competing magnet designs meet this important goal.

A7.6.2 Beam abort system

Because the 3T ring is nearly twice as large as the 6T ring, the abort kickers must remain "on" and stable for twice as long. This presents no fundamental design problem. Similarly, the kickers must be capable of twice the energy dissipation, and the beam dump must successfully contain twice the beam energy. The abort systems for the two cases are contrasted in somewhat greater detail in Appendix 6.1.

A7.6.3 Control system

The control system has virtually no impact upon the magnet type selection process, and is mentioned here only for completeness. Although the 3T design will require data paths that are roughly twice as long, the scale of the SSC is already such that time-critical operations must be controlled locally and synchronized by a master clock. The control system provides the link to reliable operations, and its early and reliable operation is absolutely essential to the successful commissioning of the SSC.

Appendix B

SSC OPERATIONS - AN ALTERNATE METHOD

F. Russell Huson

The operation of the SSC will require new ideas to modernize the operation relative to present accelerators (i.e., Fermilab, BNL). With new accelerators, (H^- ion source, rfq, 440 MHz drift tube linac, high-beta linac structures, 5 Hz 100 GeV booster and a 2 TeV superferric booster) the complete injector system can be designed with efficient operation in mind. Services such as mechanical, electrical, RF, controls, cryogenics, etc., can be shared between these machines and the main SSC.

One could set up a division with 500 people to operate the complete accelerator facility. The lab would be operated similar to KEK and DESY, not as Fermilab and BNL. That is, all possible items would be manufactured by industry, thus eliminating the need for large fabrication capability that exists at Fermilab and BNL. A breakdown of personnel for the 3T (6T) accelerator would be:

Experts		General Service		(6T)
Ion Source	3	Mechanical	50	(60)
Linac	7	Electrical	50	(60)
Booster 1	10	Cryogenic	50	(60)
Booster 2	20	Controls	50	(60)
Main SSC	50	RF	50	
Theory/R&D	20	Safety & Admin.	50	
Special Function	40	Miscellaneous	50	
	150		350	(390)

This compares to the 900 people estimated in Appendix 6.11-1.

The experimental program should be handled in a similar manner, with more fabrication being done in industry and at the universities. This would reduce the manpower by another 230 people, leaving a total of 2000.

The total operating budget would be less than $200 million per year, of which about 60% is for the accelerator facility and 40% for experiments.

The philosophy of this machine would be that the operating manpower is proportional to the complexity of the accelerator. A comparison of the 3T two-in-one (type C) and 6T one-in-one (type D) accelerators follows:

Magnetic Field	3T two-in-one	6T one-in-one
Relative Magnetic Stresses	1	4
Refrigerator Load	24.5 MW	32.7 MW
Total Cryogenic Length	164 km	196 km
Tunnel Length	160 km	100 km
Number of Dipole Units	3990	8000

It is estimated that these complications would require 10 more people in each of the appropriate service groups for operation of the 6T accelerator.

The power costs for main rings as described in the RDS, as well as for a ring of the new type D magnets, are given in Appendix 6.11. However, a different scenario for the 3T (type C) ring permits much greater economy. The revised power costs for the 3T ring are based on using 12 refrigerators around the ring and 4 power supply stations. Also a 20°K helium shield is used. Table A8-1 shows the revised power supply figures, while Tables A8-2 through A8-4 (revisions of tables from Appendix 6.11) correct cryogenics costs and incorporate our proposed manpower changes.

Thus the overall operation of the 3T system would cost about 5% less than the 6T.

AB-3

Table B-1
SSC Power Requirements
Magnet Power Supply Systems

Basic assumptions:

1) SC switches require 2V at full current
2) Warm busses require 0.5V at full current
3) Filters require 0.5V/kA
4) All equipment located at surface

Operation at 3 Tesla

	Current	SCR Switches	Warm Busses	Filters	Power
Inner coils	11 KA	3 x 2V	4 x 0.5V	1 x 5.5V	0.149
Outer coils	10 KA	3 x 2V	4 x 0.5V	1 x 5V	0.130
Trim coils	2.5 KA	3 x 2V	4 x 0.5V	1 x 1.25V	0.023
Return buss	3.5 KA	-	2 x 0.5V	-	0.004
Quad coils	3 KA	4 x 2V	8 x 0.5V	1 x 1.5V	0.040
Power (MW)		0.165	0.063	0.118	0.346

Total flat-top power = 0.346 MW x 4 sectors x 2 bores

Total flat-top power = 2.768 MW

Ramping Requirements

	Current	Inductive Voltage
Inner coils	11 KA	45 V
Outer coils	10 KA	50 V
Trim coils	2.5 KA	20 V
Quad coils	3 KA	50 V
Power (MW)		1.195

Total ramping power = 1.195 MW x 4 sectors x 2 bores

Total ramping power = 9.56 MW

Installed Power Requirements

Total installed power = ramping power + flat-top power

= 9.56 MW + 2.768 MW

= 12.33 MW

Table A8-2

SSC Operations Cost
(FY 1985 dollars)*
(Modified from Table 6.11-1)

Category	Manpower (FTE)	Labor (M$)	Purchases (M$)	Power† (M$)	Power† (MW)
Physics Research	300	12.0	3.1		
Injector Systems	‡		14.8	9.0	23
Collider Cryogenics	‡		3.6(3.0)	14.1(10.9)	32.3(25.0)
Collider Other	‡		15.0(12.0)		
Magnet Power				0.8(1.2)	2.0(3.0)
RF Power				2.3(2.3)	6.0(6.0)
Misc. Power				0.9(0.9)	2.4(2.4)
Experimental Areas	200	7.3	6.0	11.7	30
Accelerator R&D	‡		3.0		
Facilities R&D	150	5.8	4.5		
Computer Operations	125	5.0	2.5		
Central Shops	50	2.0	1.5		
Building Power				5.2	12
Subtotal	1365(1325)	54.2(52.9)	54.0(50.4)	44.0(41.2)	107.7(101.4)
G&A (40%)	546(530)	21.8(21.3)	21.6(20.2)		
TOTAL	1911(1855)	76.0(74.2)	75.6(70.6)	44.0(41.2)	

SUM = 195.6 (186.0)‡

---

*Costs for 6 Tesla one-in-one design, with numbers in parenthesis for a 3 Tesla cryogenically coupled dual design.

†Power costs at $50/MWH.

‡Total accelerator manpower as outlined in the text is 500 people for the 3T two-in-one superferric ring and 540 people for 6T one-in-one ring.

Table A8-3

Steady state heat loads.

(Modified from Table A6.11-4)

	Per Refrigerator				Total			
	6.5T(1) (A)	5T(1) (B)	3T(2) (C)	6T(3) (D)	6.5T (A)	5T (B)	3T (C)	6T (D)
4.5°K (kW)	4.35†	2.05	0.68	2.25	52.2	24.6	16.4	27.0
20°K shield (kW)	--	2.40	1.20	2.60	--	28.8	28.9	31.2
80°K (kW)	20.9	24.0	11.9	24.0	251	288	286	288
Liquid He‡ (liters/hr)	210	260	180	340	2532	3120	3120	4080

1. Reference Designs Report.

2. "Refrigeration System for the SSC 3T Cold Iron Magnet System," CCI Report 599-103, 19 March 1984.

3. "Budgeted Heat Loads for Design D," C. Rode, FNAL, unpublished report dated 11 March 1985 (Appendix 4.8 of this report).

*This includes synchrotron radiation, the heat leak of supports, thermal radiation, valves, etc., and 50 watts per interaction region going into each neighboring cryogenic loop.

†The power figure of the RDS for Design A is 4872 watts. This is decreased by 520 watts, and added back as 210 liters/hr of liquid helium for lead cooling.

‡Assumes 0.06 g/s (1.8 ℓ/hr) per kA per lead.
Design D has estimated a total lead cooling (including correction elements) of 4080 liters/hr, corresponding to 2.27 x 10^6 amps. Of this, 1.15 x 10^6 amps is due to the main 6 kA power leads, corresponding to 8 power leads per aperture per refrigerator. For Design C, we have at each of 4 power supply stations 8 - 11kA leads, 8 - 10kA leads, 8 - 2.5kA leads and 8 - 3.5kA common return leads, plus 16 - 3kA quad leads for a total of 1 x 10^6 Amps. It is necessary to have 1800 ℓ/hr for leads, therefore the 3120 ℓ/hr provides excess liquid for such things as the correction leads.

Table A8-4

AC power requirements for main ring cryogenics.

(Modified from Table A6.11-5)

	Carnot efficiency	Fraction of Carnot	Overall efficiency	6.5T (A)	5T (B)	3T (C)	6T (D)
4.5°K (MW)	1.52%	17%	0.25% = 0.387 KW/W	20.5	9.5	6.4	10.5
20°K shield (MW) (from 4.5°K liquid)	1.52%	20%	0.30% = 0.329 KW/W	--	9.5	--	--
20°K shield (MW) (from 15°K gas)	5.3%	20%	1.05% = 0.095 KW/W	--	--	2.75	3.0
80°K (MW)	24%	25%	6.00% = 0.017 KW/W	4.3	4.9	4.9	4.9
Liquid He (MW)		0.83 KW/(liter/hr)*		2.1	2.6	2.6	3.4
Total (MW)				26.6	26.8	16.7	21.8

*CCI Report 593-101 (1 November 1983).

APPENDIX 6

SSC-SR-1010

The Superconducting Super Collider

Final Report
Magnet Technical Review Panel

July 25, 1985

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ABSTRACT

The Magnet Technical Review Panel has had two series of meetings. The first occurred in the fall of 1984, and in an extensive series of meetings lasting more than ten days, carried out a review of the magnet R&D program for the SSC. The accomplishments of FY84 and the plans of FY85 were studied, and an Interim Report summarizing our studies was written. A by-product of this series of meetings was the proposal for a new style magnet, type D, by a consortium of BNL, FNAL, and LBL.

In April, 1985, Dr. M. Tigner again convened the panel with slightly different membership to review the state of cable development, to report on the state of development of the individual styles of magnet, and to enumerate the time and manpower effort to complete the preprototype R&D prior to style selection.

The committee finds that:

1. The R&D program for superconducting wire and cable has produced spectacular results. The current density of commercially available NbTi cable equals 2600 A/mm^2, and may become even higher. Magnets using this conductor and operating at 4.2K routinely achieve fields greater than 6 T.
2. The technology for superconducting magnet design has a solid base. Good computer codes exist for magnet stress analysis, the behavior of a magnet under quench, and for relating random and systematic errors in magnetic field to the magnet structure. The technological base is widespread, and good communication exists between the various R&D centers.

3. No magnet-related problems were found that would threaten achieving a successful design for the SSC. The present technology is such that any of the proposed magnets can be successfully evolved to the preproduction stage. However, the remaining R&D is style specific and has a strong interaction with the overall accelerator design. If a style choice can be made now, it will narrow the scope of the remaining engineering R&D and thus conserve funds, make optimum use of the available intellectual resources, and expedite the design of the SSC.

Although the committee did agree on the R&D program necessary to bring any specific magnet design to a preproduction stage, it did not come to a consensus for estimates of the time and manpower required. In retrospect this was probably predictable. The future evolution of the magnet is inextricably tied to questions of machine lattice, aperture, operation, and cost--all of which were outside of the scope of the charge to this committee. A major advantage of the style selection will be to allow all of the resources to focus the engineering R&D on a single magnet style in a manner coherent with the overall machine design program. This is badly needed if the SSC program is to proceed in a timely and aggressive manner in the light of the presently approved funding for FY86.

I. Introduction

I.A. Meetings in 1984

The Technical Magnet Review Panel was first appointed by Dr. Maury Tigner, Director of the Central Design Group, in the fall of 1984. The charge and membership of that committee are given in Appendix A, and the charge is given below:

1) Delineate for each design type that minimal set of technical data which is needed for the design type selection process and which can only be obtained from models and prototypes.

2) Review critically and report progress, from October, 1983, to date, of each of the three major design types.

3) Review critically plans for FY85 in light of (1) and, as appropriate, suggest changes which may enhance their effectiveness.

4) Write a report setting forth the results of (1), (2), (3), in a systematic fashion.

A series of ten meetings in October and November, 1984, were held at Brookhaven National Laboratory (BNL), Fermi National Accelerator Laboratory (FNAL), Lawrence Berkeley Laboratory (LBL), and Texas Accelerator Center (TAC), and an interim report was produced in response to the charges set forth above.

The meetings served as an excellent forum for the major participants to review and discuss R&D techniques common to all the various styles of magnets.

I.B. Meetings in 1985

In April, 1985, the committee with a slightly different membership was again called into session. The membership is given in Appendix B and the charge reproduced here:

1. Review magnet and cable development programs at FNAL, LBL, and TAC.
2. Write a report evaluating the technical status of dipole and quadrupole magnet design and development work for the 1-in-1 and 2-in-1 low and high-field magnet styles. For each style enumerate the R&D remaining before each style can prudently be carried to the full-scale prototype stage. This enumeration should include an estimate of the time and manpower effort needed to complete the pre-prototype R&D. The report should include a detailed account of model tests for the various designs.
3. Evaluate and report on the status of superconducting cable development and enumerate further development objectives which could reasonably be expected to be complete in time to have a beneficial impact on SSC magnet cost, reliability and ease of operation. The report should be complete by July 25, 1985.

We have held two meetings: the first was at TAC, July 1-2, and the second at BNL, July 11-12.

I.B.1 Meeting Held July 1-2 at TAC

At the first meeting, the progress on magnets was again reviewed. A new design, D, proposed by a consortium of BNL, FNAL, and LBL was reviewed. This magnet is a cos Θ, cold iron, 6.5 T magnet with a 4-cm bore and uses collared coils.

This made five different designs of magnets to be considered. They are:

1. Design D 1-in-1, cold iron, 6.5 T, 4-cm bore. Consortium BNL FNAL, and LBL.
2. Design B 1-in-1, no iron, 5.5 T, 5-cm bore. FNAL revised.
3. Design A 2-in-1, cold iron, 6.5 T, 4-cm bore. BNL, and LBL.
4. Design C 2-in-1, superferric, 3 T, 3.5 cm x 2.5 cm. TAC.
5. Design C* 1-in-1; superferric, 3 T, 3.5 cm x 2.5 cm. TAC.

The committee concentrated its attention on types D and C. The reason for this is that the designs for these two styles are the most advanced. In addition all of the cos θ style magnets now propose to use collared coils and thus the variations in these three magnets appear in the cryostat design and for case A in the magnetic coupling between the two apertures. Therefore, programs for types A and B were viewed as perturbation of the program proposed for D. Design C* is viewed as a perturbation of C, since the magnetic coupling is minimal in this design, and if anything, the assembly may be easier. Very little effort has gone into specific C* design.

After reviewing each of the two styles, the committee spent considerable time reviewing the status of each design and what areas remained to be clarified by further R&D. A list was made by the committee of those areas for each style that would require more R&D. The various "proponents" of each style were then asked to respond in writing at the BNL meeting on their view of how and when this R&D would be carried out.

I.B.2 Meeting Held July 11-12 at BNL

The body of the report was constructed at BNL. There was good agreement among the members concerning the areas of each design that would require further engineering R&D information to bring it to the level of preproduction prototype if it were selected. We include this information in tabular form as well as the "proponents" written responses mentioned above.

However, while we could reach agreement as to where the R&D effort would be needed, we found it impossible to reach agreement upon how much may be required to bring an individual style to the preproduction stage. Thus, the programs presented in Section V are only illustrative of a program that does not get hung up on a knotty problem. This report fails in giving any estimate of the contingency required in the various programs. In addition the committee declined to present here the range of views held by its various members.

I.C. Overview

Section II of this report reviews the status of superconducting magnet technology. The thrust of this section is that the general principles that underlie the design of a magnet are now well understood and widely dispersed within the community. References are given where possible to either published data or data on file with the Central Design Group (CDG).

Section III includes a brief description of the various magnet styles. These descriptions are abstracts in the case of B and D of documents on file with the CDG at LBL. Style A and C are described in the Reference Designs Study.

Section IV is a report on the status of the superconducting wire and cable development.

Section V presents a discussion of the R&D programs necessary to bring the individual designs to a preproduction stage. The appendices contain some of the documentation used in preparing this section.

It is the opinion of the committee that a sufficient R&D base now exists for a style choice and that if the selection is made now it will narrow the scope of the R&D effort. This will conserve funds, make optimum use of the intellectual resources available in the community, and will result in expediting the technical feasibility for the SSC.

The successful construction of large numbers of accelerator quality superconducting magnets has been demonstrated by the successful operation of the Tevatron. It was emphasized during the reviews carried out by the committee that the technology of magnet fabrication is now widely spread and well understood at the major U.S. centers for magnet development: BNL, FNAL, LBL, and TAC.

The R&D program after the style choice will be directed toward using this broad technical base in collaboration with industry to develop a preproduction prototype of a magnet that has manufacturability and meets the requirements of the SSC. It is the purpose of the next section to document that the technological base is competent to carry out this task.

II. PRESENT STATUS OF MAGNET TECHNOLOGY

Superconducting magnet technology can be broken down into the following areas:

1. Cable/conductor technology.
2. Conductor support structure.
3. Quality control and field errors.
4. Quench protection.
5. Cryostat design and cryogenics.

In the following we will give a brief overview of these subjects with the intention of demonstrating the widespread, high-level technology that has been developed within the community. It is the invaluable heritage of the extensive superconducting magnet R&D program that has been pursued in the U.S.over the last ten years and an asset that permits constructing the SSC with confidence.

II.A. Conductor Technology

Spectacular progress has been made in increasing the current density that is commercially practical to achieve in a NbTi superconducting cable (Ref. 1). This is documented in Fig. II.1. which shows the critical current density versus magnetic field for several conductors. The Tevatron cable is the lowest curve. The last two years have seen the fruition of an R&D program supported by the DOE and involving industry, national laboratories, and the University of Wisconsin. The result has been a much better understanding of the metallurgy involved in producing NbTi filaments.

Figure II.2a shows photomicrographs of the NbTi filaments in the new cable versus that typical of the Tevatron shown in Fig.II.2b. The much smoother, more uniform filament shown in Fig. II.2a presents the possibility of drawing the wire down to a smaller filament size. Multi-stage heat treatments have

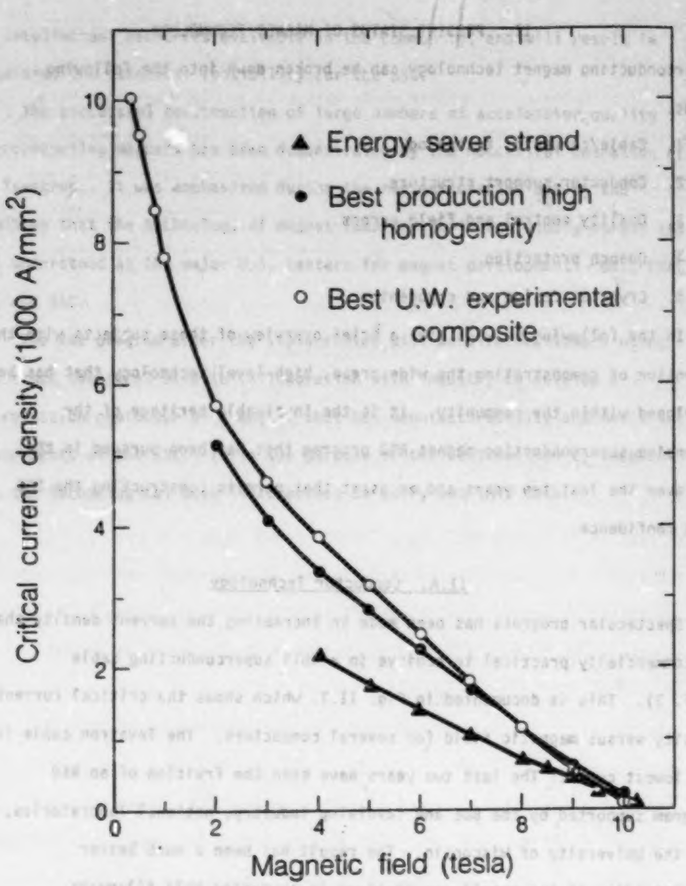

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Fig. II.1 Curves showing progress in raising the J_c of NbTi.

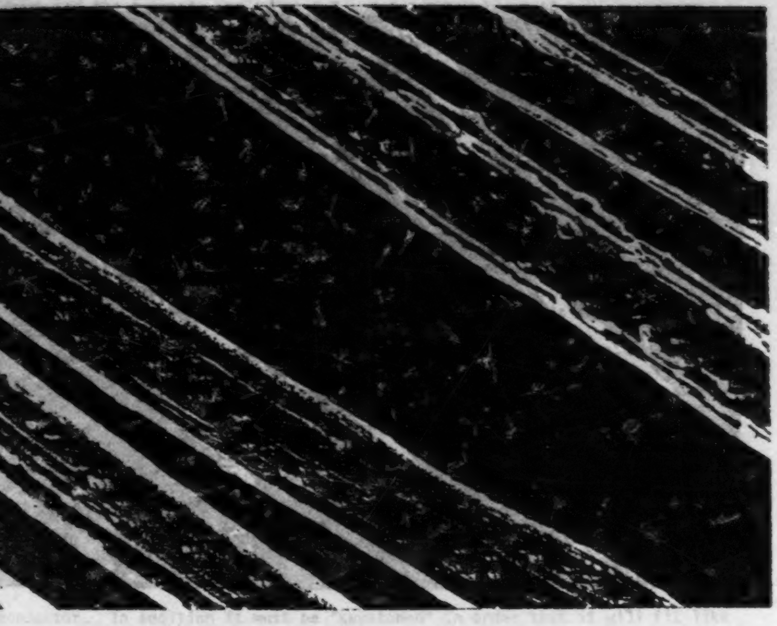

Fig. II.2a SEM micrograph of filaments from Billet CB1710 at 4μm filament diameter. $J_c(5T) = 2640$ A/mm^2

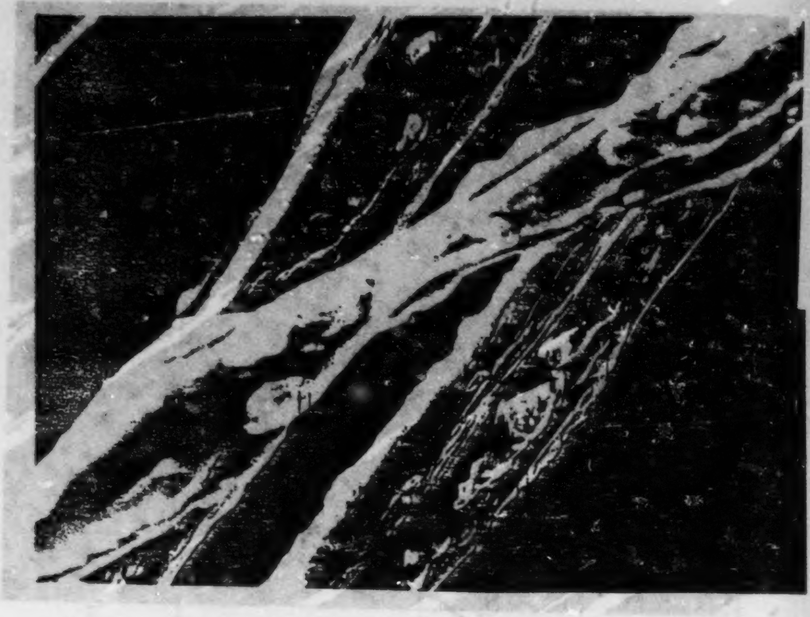

Fig. II.2b SEM micrograph of filaments showing uneven filament diameter and large nodules of intermetallic.

increased the current density at 5 T and 4.2 K by almost 50 per cent (2700 A/mm^2) compared to the FNAL cables (1800 A/mm^2); this has been accomplished commercially on a large scale for superconducting strand with 20μ filaments. Commercial production of cable with filaments less than 5μ in diameter and current densities of 2600 A/mm^2 looks very promising.

The above represents a good example of the impact of magnet style on the R&D program. All magnets benefit from the increased current density in the superconductor. The cos θ style will also benefit from a smaller persistent current sextupole field at injection if the filament size is reduced since the value of b_2 is proportional to filament diameter. However, other techniques are readily available for correcting this field, and the R&D must be directed at comparing the commercial cost of producing wire with small filaments versus the cost of adding distributed superconducting correction coils. If the superferric magnet style is chosen, further development of small filament size would not be necessary for the dipoles.

The cable used in magnets is made from many strands of composite conductor. In addition it must be "keystoned" in order that it will fit like wedges in an arch if it is used in a cos θ style magnet. After the keystoning operation, the cable is insulated with a Kapton wrap. Regardless of the magnet style this cabling operation must produce a well insulated package with precisely controlled dimensions and one in which the current-carrying capacity is not degraded by having filaments broken during the manufacturing process. Research at LBL in collaboration with industry has resulted in cables with as many as 36 strands compared to the 23 strand cable used in the Tevatron. Modern cable with higher current as well as higher current density has resulted in SSC model magnets that operate at over 6.5 T at 4.5K compared to the Tevatron that operates at about 4 T.

The conductor R&D program has produced excellent facilities at the National Laboratories for making measurements on short samples of the various properties of the conductor (Ref. 2). Widespread agreement exists on the measuring techniques to be used and on the interpretation of the data. This represents an important step in the ability to accurately define the specification of the conductor for industrial production.

An example showing the sophistication in instrumentation presently available is given in Fig. II.3. These measurements were made by clamping a hairpin of cable in a fixture and inserting the assembly into a dipole. B may be oriented either perpendicular or parallel to the wide face of the cable. The voltage drop across the cable versus the current through the cable is measured. Near the critical current the resistance of the sample increases very rapidly from the superconducting state and follows an expression of the form $R = KI^n$. The value of I_c is defined as that current where the resistivity of the cable is 10^{-14} ohm-meters. The printout shown in Fig. II.3 gives the date, the value of n, I_c, B and the temperature. Figure II.4 shows the results for a 30 strand cable prepared at LBL and tested at BNL for style D magnets. Two directions of B are measured and compared with 30 times the current measured for a single strand of virgin wire. Some degradation due to cabling is evident as well as dependence upon the direction of B. High quality measurements such as those shown in Fig. II.4 are important in studying the effects of compaction during manufacture on the current-carrying capacity of the cable (Ref. 3). In addition they provide the most effective way to effect quality control on the superconductor strand as well as the completed cable. Finally for magnets constructed with presently developed techniques there is a good correlation between the short sample test of a cable and how it performs in a completed magnet (Ref. 4).

```
RUN 3823    TAC    B:SPOOL    Sp: 3             Probe:B             5-5-85
---------------------------------------------------------------------------
Field = 50kG            Dia.= .0268in.          C/S= 1.21          Mfr C/S= 1.3
---------------------------------------------------------------------------
 Amps   uVolts   Rho       Amps   uVolts   Rho       Amps   uVolts   Rho
  1.0     1.7    74.2      350.4    1.6     .2       442.7   11.1    1.2
 59.8     1.0     .7       382.0     .6     .1       445.4   14.0    1.5
105.3     1.4     .6       401.8    1.8     .2       450.9   23.0    2.5
155.8     1.6     .4       414.4    1.0     .1       454.5   32.5    3.5
201.0     1.2     .2       427.6    2.0     .2       459.2   54.0    5.7
256.7      .6     .1       434.0    4.9     .5       461.6   70.2    7.4
300.8      .7     .1       438.7    7.1     .8       463.2   84.4    8.8

Ic1= 441.7   Iq= 465   n= 45.1    Jc= 2683 A/mm2
```

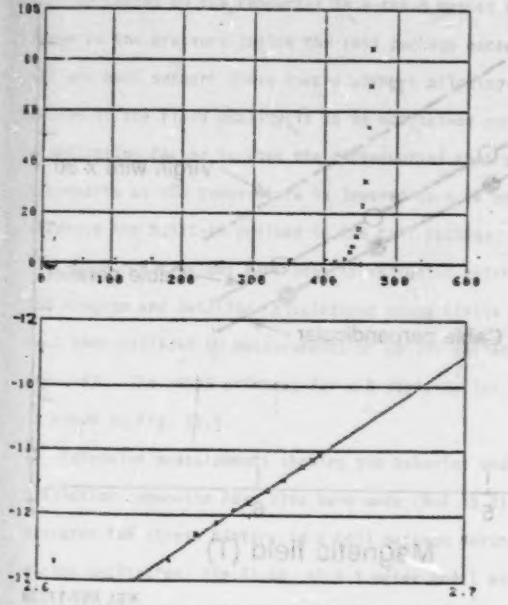

Fig. II.3 Sample data sheet from BNL wire critical current measurement. The upper graph shows V in μV vs. I in A. The lower graph shows log ρ vs. log I.

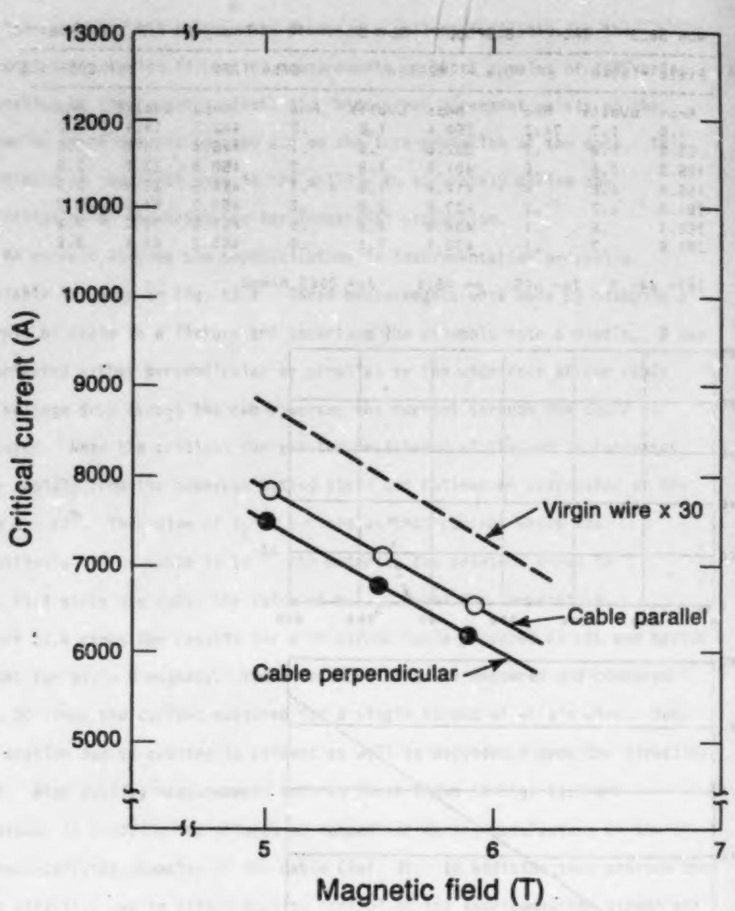

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Fig. II.4 Critical current vs. magnetic field results for outer Design D cable XT-013-3012HH and component wire.

II.B. Conductor Support Structure

In order to achieve an accurately shaped magnetic field, the conductors must be located very accurately. They also must not move with thermal or magnetic stress. The cos Θ magnets and superferric magnets are considerably different in the magnitude of the forces that must be constrained and the dependence of the field shape on coil and support dimensions; therefore, we will consider the two styles separately and contrast their differences.

II.B.1. Cos Θ Support Structure

The forces on the conductor in a cos Θ magnet excited to 6 T are very large as the pressure inside the coil package exceeds 2000 psi. The coil collars must support these forces without allowing appreciable conductor motion if the field quality is to be maintained during excitation. A complicating factor is that the differential contraction of the various components as the temperature is lowered to 4.5K may either increase or decrease the built-in preload on the coil package.

These two problems have been investigated extensively in the cos Θ magnet R&D program and detailed calculations using finite element stress analysis have been verified by measurements of collar deflection for this style magnet (Ref. 5). The ANSYS printout for a B style collar as calculated at Fermilab is shown in Fig. II.5.

Extensive measurements showing the behavior under load of the cable plus insulation composite have also been made (Ref. 5.1). Recently LBL has measured the stress history in a coil package during cooldown, Fig. II.6a, and during excitation, Fig.II.6b, of a 1 meter model magnet (Ref. 6). The different curves in Fig.II.6b show the relief of internal stress during training of a magnet and its I^2 dependence during excitation.

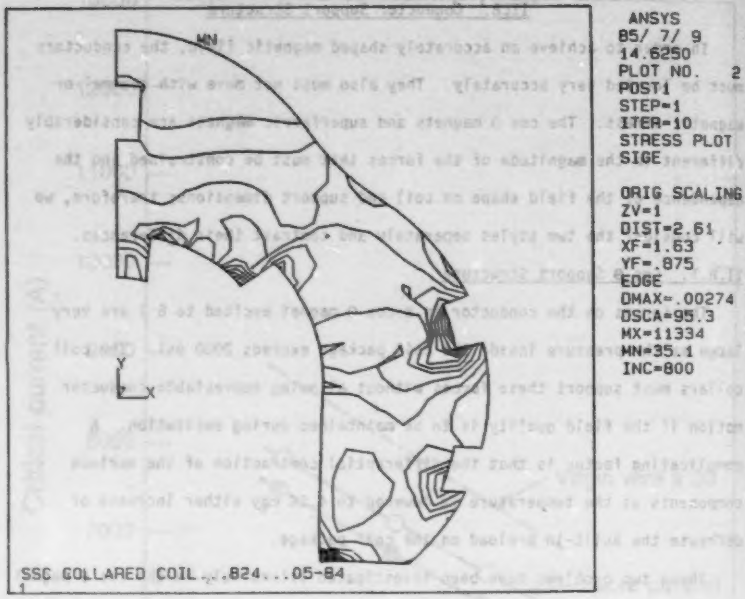
MN
MX
Y
X
ANSYS
85/ 7/ 9
14.6250
PLOT NO. 2
POST1
STEP=1
ITER=10
STRESS PLOT
SIGE
ORIG SCALING
ZV=1
DIST=2.61
XF=1.63
YF=.875
EDGE
DMAX=.00274
DSCA=95.3
MX=11334
MN=35.1
INC=800
SSC COLLARED COIL ...B24...05-84
1

Fig. II.5 ANSYS output for style B collar.

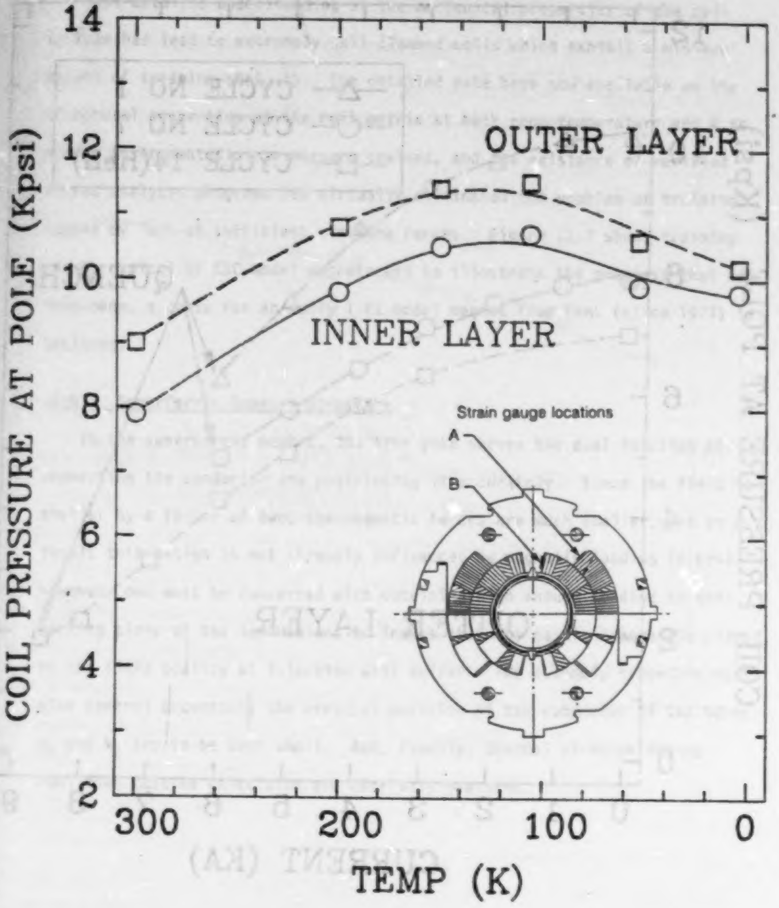

Fig. II.6a Change in pressure at the key during cool down from room temperature as measured by stress gauges located as shown in the insert. The collars were aluminum and contracted during cool down more than the coil package with a resulting increase of preload.

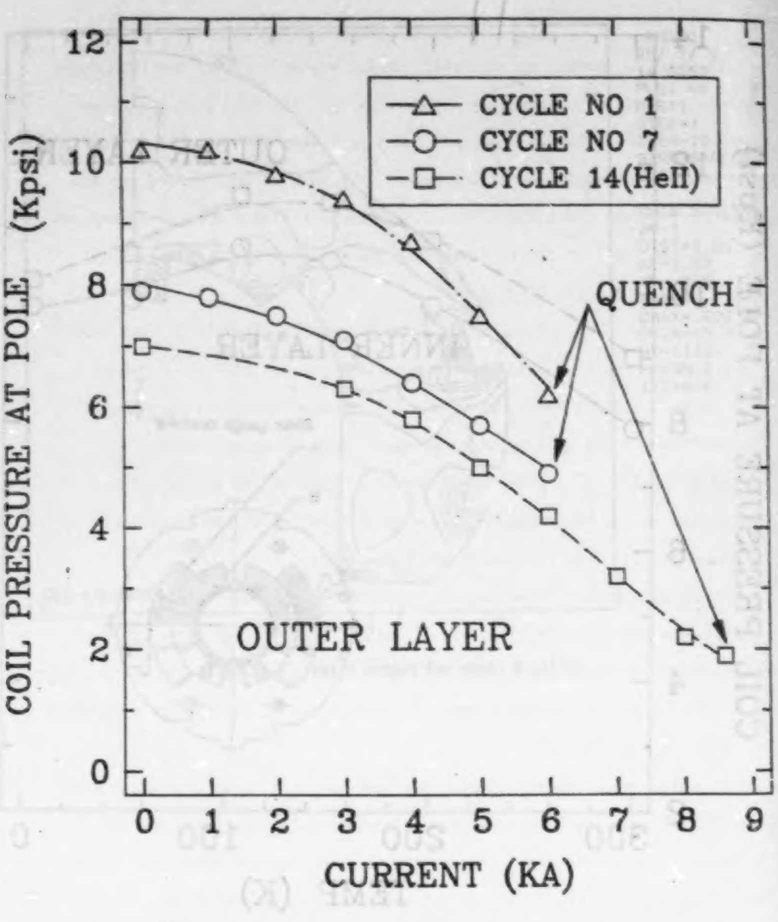

Fig. II.6b Coil clamping pressure at the points B shown in Fig. 6a. The different curves exhibit the decrease in pressure at the key proportional to I^2 as expected. When the coil quenches, the internal stress is redistributed and the coil "trains."

This detailed understanding of the mechanical properties of the coil package has lead to extremely well clamped coils which exhibit a minimum amount of training (Ref. 7). The detailed data base now available on the structural properties of the coil matrix at both room temperature and 4.5K, modern instrumentation to measure preload, and the existence of verified stress analysis programs has virtually eliminated the problem of training caused by lack of sufficient clamping forces. Figure II.7 shows training curves typical of SSC model magnets and to illustrate the progress that has been made, a curve for an early 1-ft model magnet from FNAL (circa 1977) is included.

II.B.2 Superferric Support Structure

In the superferric magnet, the iron yoke serves the dual function of supporting the conductor and positioning it accurately. Since the field is smaller by a factor of two, the magnetic forces are much smaller, and as a result this design is not strongly influenced by magnetic loading forces. However, one must be concerned with obtaining high enough loading at the parting plane of the laminations to insure that the gap is adequately closed or the field quality at injection will suffer. The assembly procedure must also control accurately the vertical position of the conductor if the terms a_1 and b_2 are to be kept small. And, finally, thermal stresses during cool down must be calculated and carefully measured.

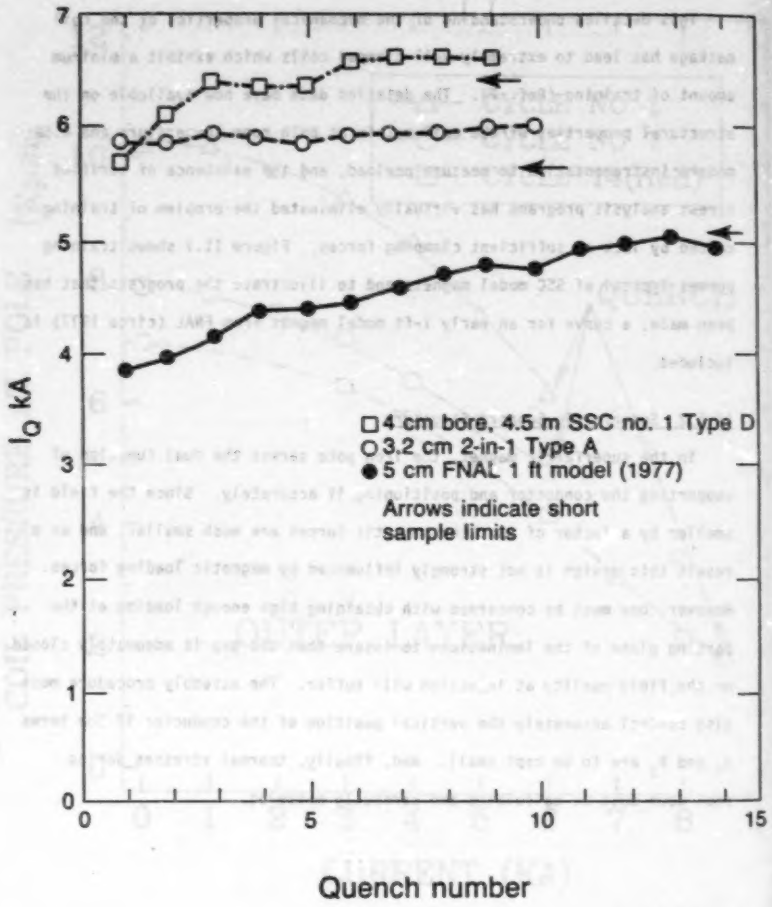

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Fig. II.7 Training history of two SSC-style 4.5 meter models compared to a very early Tevatron 1-foot model magnet. The arrows indicate the expected short sample limit.

II.C. Quality Control and Field Errors

Controlling the quality of the magnetic field in the dipoles and quadrupoles of the SSC is one of the primary concerns of the magnet program. The magnitude of the random and systematic errors is measured by the coefficients a_n and b_n in the expansion for the field on the median plane of the dipole

$$B_y = B_0 \sum_0^\infty b_n x^n \qquad b_0 = 1$$

$$B_x = B_0 \sum_0^\infty a_n x^n$$

Similar equations exist for the gradient inside a quadrupole.

Calculations show that extraordinarily uniform fields are possible if the conductors are placed in the correct location; however, in the real world, a number of effects leading to both systematic and random error fields must be dealt with in magnet design. These effects are different for each style magnet and will be discussed separately below. Systematic errors are considered first and involve primarily the properties of the superconductor and of magnet iron which are amenable to measurements in the laboratory. These data can be used quite successfully with computer codes to calculate the systematic error fields.

Random errors are a more difficult problem. They depend not only on the magnet style, but also its size and the intimate details of the processes and tooling used in its manufacture. A "general model" for a given style may be useful at the early stages of the machine design for estimating the aperture required. However when the manufacturing has began, a specific error model is required in order to determine the specifications and set the tolerances for all of the components consistent with having the final magnet meets its design criteria.

We show below that general models are available for the different designs. A specific error model will only come as the manufacturing process for the final magnet is defined.

II.C.1 Systematic Errors

For the cos θ style the major systematic error is the sextupole and decapole fields at injection due to persistent currents in the superconducting filaments. For the superferric magnet, these two multipoles also dominate the systematic errors, but they are most important at high field and are caused by saturation of the iron plus the intrinsic field from the coils after the iron is saturated (Ref. 12). Methods exist for correcting these fields in both cases.

For the cos θ magnets, a straight forward bore tube correction coil such as was successfully tested for CBA magnets could be used. Alternatively since these fields are proportional to the filament diameter, it it possible to reduce them by manufacturing strand with smaller size filaments. A great deal of R&D effort has gone into understanding the effects of persistent currents and constructing a model that accurately predicts their effects (Ref. 9). BNL has the facility to measure the magnetization of a sample of superconductor. Data from such a measurement are shown in Fig. II.8. The measured magnetization data from BNL shown in Fig. II.9a are used to predict b_2 for a model magnet constructed and measured at LBL. A comparison of the measured and calculated values of b_2 is shown in Fig. II.9b.

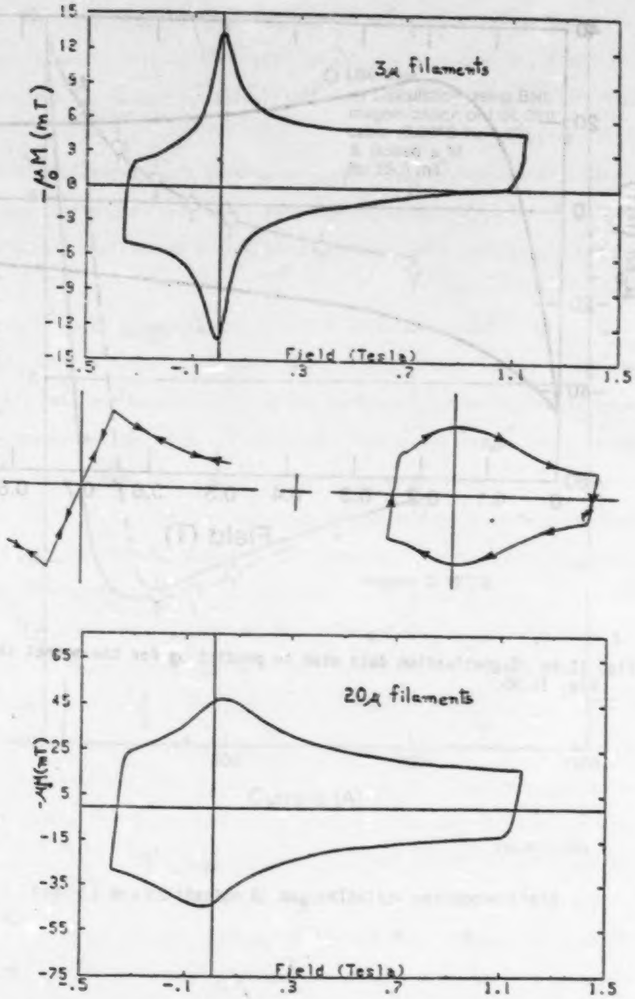

Fig. II.8 The results of reversible and hysteresis effects on the magnetization of samples with two different filament sizes (3μm and 20μm).

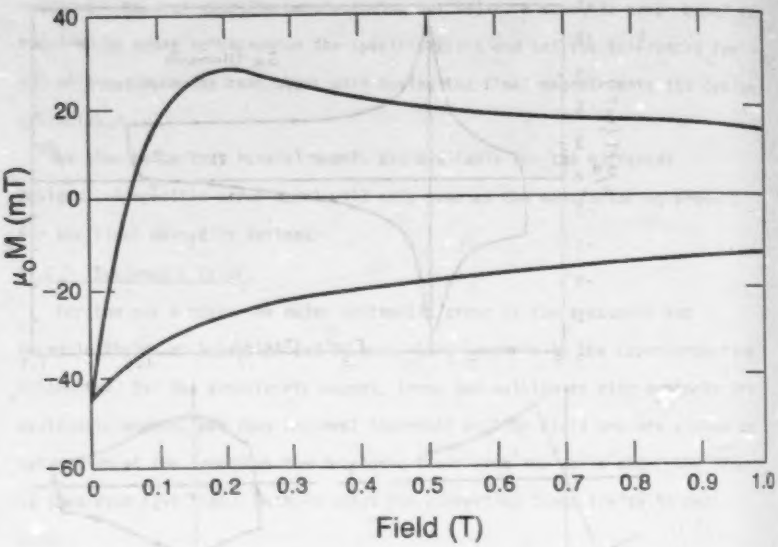

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Fig. II.9a Magnetization data used to predict b_2 for the magnet shown in Fig. II.9b.

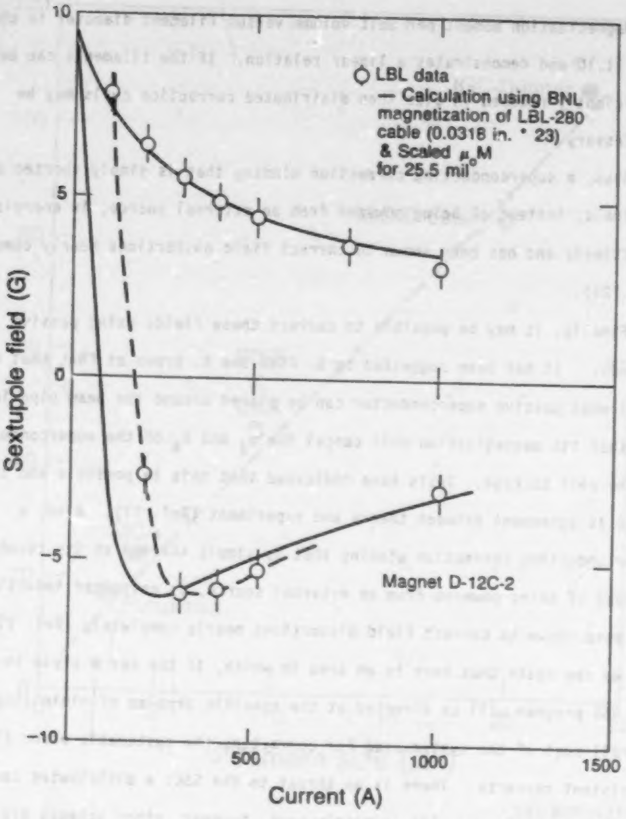

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Fig. II.9b C5 (Design D) magnetization sextupole field.

Magnetization moment per unit volume versus filament diameter is shown in Fig. II.10 and demonstrates a linear relation. If the filaments can be sufficiently reduced in size then distributed correction coils may be unnecessary.

Also, a superconducting correction winding that is simply shorted at its terminals, instead of being powered from an external source, is energized inductively and has been shown to correct field distortions nearly completely (Ref. 21).

Finally, it may be possible to correct these fields using passive methods. It has been suggested by G. Fisk and B. Brown at FNAL that some additional passive superconductor can be placed around the beam pipe in such a way that its magnetization will cancel the b_2 and b_4 of the superconductor in the coil package. Tests have indicated that this is possible and that there is agreement between theory and experiment (Ref. 17). Also, a superconducting correction winding that is simply shorted at its terminals, instead of being powered from an external source, is energized inductively and has been shown to correct field distortions nearly completely (Ref. 21).

We see again that here is an area in which, if the cos θ style is chosen, the R&D program will be directed at the specific problem of minimizing the overall cost of the system used for correcting the systematic error fields and persistent currents. There is no threat to the SSC: a distributed correction coil can be built and will certainly work; however, other schemes are available for performing the same function.

The superferric magnets have three different windings and through control of the total current, plus the two independent ratios, the central field can be set to a given value and the systematic values of b_2 and b_4 tuned out.

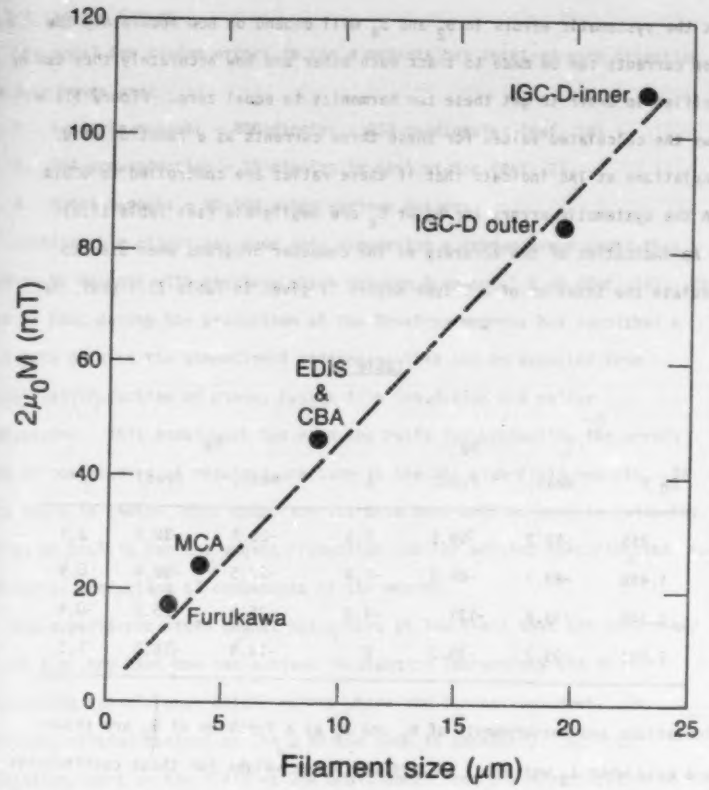

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Fig. II.10 Variation of measured magnetization with filament size for samples with transport current $J_c \approx 2500$ A/mm^2 (Ref. 9b).

Thus the systematic errors in b_2 and b_4 will depend on how accurately the three currents can be made to track each other and how accurately they can be specified in order to get these two harmonics to equal zero. Figure III.8 shows the calculated values for these three currents as a function of B. Calculations at TAC indicate that if these ratios are controlled to 0.01% then the systematic errors for b_2 or b_4 are negligible (see Table II.2).

An indication of the accuracy of the computer programs when used to calculate the behavior of a C type magnet is given in Table II.1 (Ref. 12).

Table II.1

	b_2			b_4		
B_0 T	Meas.	Pred.	Δ	Meas.	Pred.	Δ
.756	-58.2	-59.5	1.3	-28.4	-30.5	2.1
1.498	-89.7	-88.3	-1.4	-37.5	-38.4	0.9
2.349	-135.8	-131.	-4.8	-25.8	-25.2	-0.6
2.981	-35.2	-35.2	0	-14.9	-16.0	1.1

Calculations and measurements of b_2 and b_4 as a function of B_0 are shown for a case when I_3 was equal to zero and large values for these coefficients would be expected. The agreement between measurement and calculation to a few units in b_2 and b_4 indicates the present accuracy of the computer codes in a case where the iron at 3 T is highly saturated. More work is required to test the ability to predict the current ratios required for setting b_2 and b_4 equal to zero. An additional systematic effect that has not been studied is that of the residual magnetization on the shape of the injection field.

II.C.2 Random Errors

The model for random errors in $\cos \theta$ magnets has received much attention. The data bases are:

1. Tevatron magnets - 800 dipoles - 250 quadrupoles (Ref. 10).
2. CBA preproduction - 10 dipoles in test string (Ref. 7).
3. Model magnets - 50-100 using various designs.

Considerable effort has gone into generating a random error model that applies to magnets with aperture sizes between 3 cm and 7.5 cm (Ref. 11). The work at FNAL during the production of the Tevatron magnets has furnished a good data base on the dimensional tolerances that can be expected from industrial production of cable, Kapton film insulation and collar laminations. This model work has been the basis for projecting the errors used in the studies of required aperture in the SSC high-field magnets. If this style is chosen, this model and its data base will be used to guide the design of tooling for the magnet production and for writing specifications for industrial production of components of the magnet.

The superferric style magnet has errors at low field that are determined by the accuracy that one can achieve in stamping laminations and in controlling the air gaps at the points where the laminations meet. In addition, careful control of the μ of the iron is necessary. At high excitation, part of the field at the orbit comes from the magnetization of the iron and part from the direct field of the coils, and therefore the field errors arise from fluctuations in the magnetization of the iron and from errors in mechanical placement of the conductor.

An error model covering the above effects has been developed at TAC (Ref. 12) using the programs POISSON and MAGNUS. Table II.2 shows the results of these calculations as they existed in July, 1985. Additional work is in progress to compute the missing numbers, i.e., odd b_n and even a_n.

The degree of confidence one can have in these calculations was discussed in connection with the results shown in Table II.1. More measurements

Table II.2 (Table taken from Ref. 12)

	B_0		b_2		b_4		b_6		a_1		a_3	
Tesla	0.15	3	0.15	3	0.15	3	0.15	3	0.15	3	0.15	3
HMC	0	0.25	0.02	0.007	0.005	0.004	0.002	0.004	0	0	0	0
VMC	0	0	0.08	0.3					0.28	0.18	0.08	.03
GS	1.5	13	2.7	0.18	0.03	0.02	0.3	0.003	0	0	0	0
CR	0	0	0.37	1.1	0.2	0.004	0.035	0.001	0	9	0	0
MV	0.01	39		0.3		0.022						
MM	0	12	0.01	0.4	0.01	0.13	0.005	0.4				
SFV	0	155	0.002	2.4		0.07		0.013				
SFM	0	71	0.004	6.3	0.004	0.36	0.005	0.22				

HMC - Horizontal misplacement of conductors (1 mil; 4)
VMC - Vertical misplacement of conductors (3.8 mil total; 1)
GS - See 1 gap spacing (0.2 mil; 2 for b_n, 4 for B_0)
CR - Current ratio (0.01%; 2)
MV - μ variations (2% at 0.15T, 0.13% at 3T; 1)
MM - Up-down μ mismatch (2% at 0.15T, 0.18% at 3T; 1)
SFV - Stacking factor variations (0.1%;1)
SFM - Up-down stacking factor mismatch (0.1%; 1)

The numbers in parentheses are the accuracies with which we believe that the corresponding error can be controlled, and the rms number of occurrences. The calculated sensitivities of the harmonic components to each error for the WF2C model are shown in the table (Ref. 12).

are clearly needed to verify the accuracy of these predictions. To date, eight magnet model bores have been measured; two 2-in-1 magnets and four 1-in-1. The magnets are of varying design and not all harmonics are available for studying errors.

If this style magnet is selected, future R&D work will involve studies of how accurately the magnetization iron can be controlled, on average, over the magnet. The precision of lamination stampings, the pressure required to close the gap at the parting plane, and the errors in conductor placement will all need more study.

II.D. Quench Protection

Quench protection for SSC magnets is necessary regardless of the style finally chosen. None of the magnets can afford the luxury of a cryostable conductor due to the high current density required. The Tevatron represents the existence proof that a large system can be protected adequately (Ref. 13); it has over 10^8 cm of cable--each centimeter of which must be monitored and protective action taken if it goes normal due to an instantaneous temperature increase from frictional motion, beam loss, or lack of refrigeration. The Tevatron uses an "active" system of protection. If a quench is detected, a subsection of the magnet system is shorted with an SCR, and a heater is fired inside the shorted magnets driving them normal. Enough conductor must be driven normal so that all of the stored energy in the subsection can be absorbed as an increase of the enthalpy of the conductor without producing a temperature increase so high that the winding is damaged.

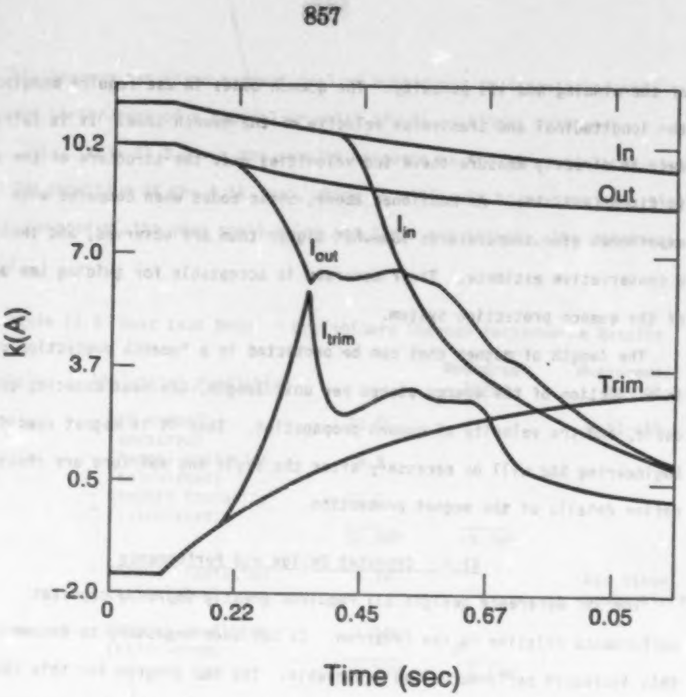
A passive system was developed for the CBA magnets and is being studied for the SSC (Ref. 7). This system utilizes cold diodes to bypass the current around the normal-going magnet and relies on quench propagation within the magnet to spread the energy loss over sufficient conductor to limit the temperature rise to safe values.

The R&D program is concentrating on obtaining good values for the quench wave velocity within the magnet structure. Once these values are known, comparison can be made between quench code predictions and actual measurements made on magnets equipped with small heaters at various spots in the magnet to trigger quenches. In the case of the cos Θ dipole data on several magnets (Ref. 14) verify these computer codes. Extrapolation from the present length magnets of about 6 meters to 16.6 meters and higher fields can be made with a certain degree of confidence.

A complicated time dependence for the magnet currents can exist if there is more than one inductively coupled loop such as occurs when the top and bottom coils of a cos Θ magnet are separately protected or, in the case of the superferric magnets, where three different loops are magnetically coupled non-linearly. This effect, if present, must be included in the quench protection code.

The calculated curves of current versus time for a passively protected 105 m long superferric magnet are shown in Fig. II.11. Calculated temperatures are in the table under Fig. II.11 (Ref. 8). At present the quench velocity has been measured in a 1 meter model and used in the computer program.

The present computer codes give an upper limit for the temperature rise of the conductor since they all use an approximation that neglects any heat removal due to vaporization of the helium in contact with the conductor. The amount of this helium is not accurately known as it depends on the compaction



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4x35 Dipole-Magnets Section Outer Coil Quench

	T(s)	θ(K)	NM	R(Ohm)	V(volts)	VQ(m/s)	Fraction
OUTER		672	44	0.0537	140	12.0	0.23
INNER	1.0	552	41	0.0561	151	15.0	0.34
TRIM		97	4	0.2492	105	24.0	1.00

Fig. II.11 Calculated currents vs. time for the three currents in a 105 m long Type C superferric magnet. The calculated maximum temperature and voltage is shown in the table above (from Ref. 8).

of the winding and its porosity. The quench codes in use require knowledge of the longitudinal and transverse velocity of the quench zone. It is fairly easy to directly measure these two velocities once the structure of the magnet is fixed (Ref. 15). As mentioned above, these codes when compared with experiment give temperatures somewhat higher than are observed, and thus gain a conservative estimate. Their accuracy is acceptable for guiding the design of the quench protection system.

The length of magnet that can be protected in a "quench protection cell" is a function of the energy stored per unit length, the heat capacity of the cable, and the velocity of quench propagation. Thus it is magnet specific. Engineering R&D will be necessary after the style and aperture are chosen to define details of the magnet protection.

II.E. Cryostat Design and Performance

The SSC Reference Designs all required greatly improved cryostat performance relative to the Tevatron. It has been necessary to document that this increased performance was achievable. The R&D program for this study has been centered at FNAL. Three separate facilities have been constructed:

1. 12 meter model cryostat assembly.
2. 6 meter model with Tevatron style collared coil assembly to study transient magnetic eddy current effects in the intermediate heat shields during a magnet quench.
3. LHe dewar instrumented to accurately measure the heat leaks in a wide variety of support devices.

In addition, a model was constructed to measure distortions caused by stress from thermal gradients that are encountered during cooldown.

This program has given a great deal of confidence that predicted and measured performance of a typical cryostat are in excellent agreement (Ref. 16). Table II.3 gives the results measured on the 12-m model cryostat. With the exception of the 4.5K load, which is difficult to measure on a single magnet because of its very small value and large end effects, the agreement is excellent.

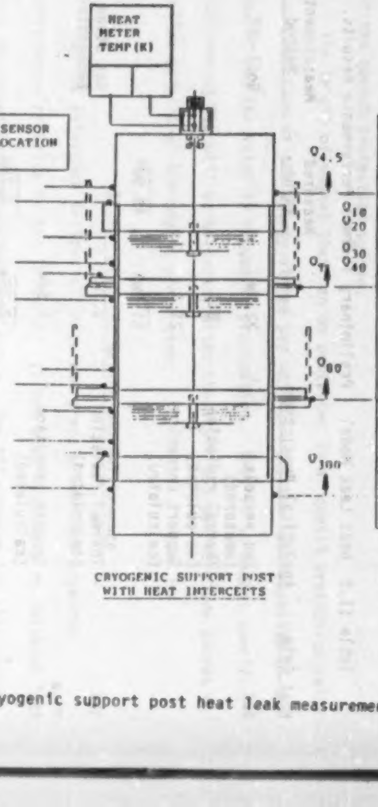
Table II.3 Heat Leak Model - Preliminary Thermal Performance Results.

Heat Gain	Analytical Prediction		Measured Value	Measurement Method
80K	- End vessels (measured)	22.0W		Boil-off
	- Thermal radiation (calculated)	8.3		
	- Support conductor (calculated)	21.2		
		51.5W[a]	55.5W[a]	
10K rise	- Thermal radiation (calculated)	0.7W		Gas steam temperature
	- Support condition (calculated)	1.54W		
		2.28W	2.28W	
4.5K	- End vessels (measured)	450mW		Boil-off
	- Thermal radiation (calculated)	2mW		
	- Support conduction (calculated)	440mW		
		892mW[a]	1060mW[a]	

[a] Total heat gain to model ... includes end vessels

This measurement is complemented by measurements in the instrumented dewar which allows a single support to be studied and the very low losses at 4.5K to be easily measured. Figure II.12 shows the results of one such measurement. Note the very small values that can be measured between the 4.5K point and the first heat intercept and their good agreement with predictions.

DESIGN TEMP (K)	MEASURED TEMP TEST DEWARM	MEASURED TEMP 10 MODEL	SENSOR LOCATION
4.5	6.3	8.3	
4.5	6.4	8.4	
5.9	7.7	9.6	
9.1	9.2	12.6	
10.0	10.3	13.2	
21.7	25.1	30.2	
74.1	77.9	91.2	
80.0	83.6	101.2	
139.1	149.2	158.6	
266.7	217.3	251.5	
100.0	278.9	281.6	
300.0	282.6	284.5	



CRYOGENIC SUPPORT POST WITH HEAT INTERCEPTS

	HEAT LEAK, Q	
	DESIGN (MW)	MEASURED TEST DEWAR
Q_{10}	21	25*
Q_{20}	80	88*
Q_{30}	153	158*
Q_{40}	240	243*
Q_{80}	4211.8	—
Q_{300}	4559.2	—

*VALUES CORRECTED TO 4.5K

Fig. II.12 Cryogenic support post heat leak measurements.

The performance of the multilayer insulation between the 80K shield and room temperature depends on the insulating vacuum. Figure II.13 shows that the MLI blankets used in these tests perform considerably better (i.e., work at a higher pressure) than previous data would indicate.

The measurements on supports and MLI are applicable to any style of magnet and indicate that the heat load budget proposed in the Reference Designs Study can be met; however the information obtained concerning distortion caused by cool down thermal stress is only applicable to magnets in the length range of 10-15 meters. Longer magnets such as proposed for the type C of ~100 meters still must be studied as no measurements of thermal distortions in such long structures exist.

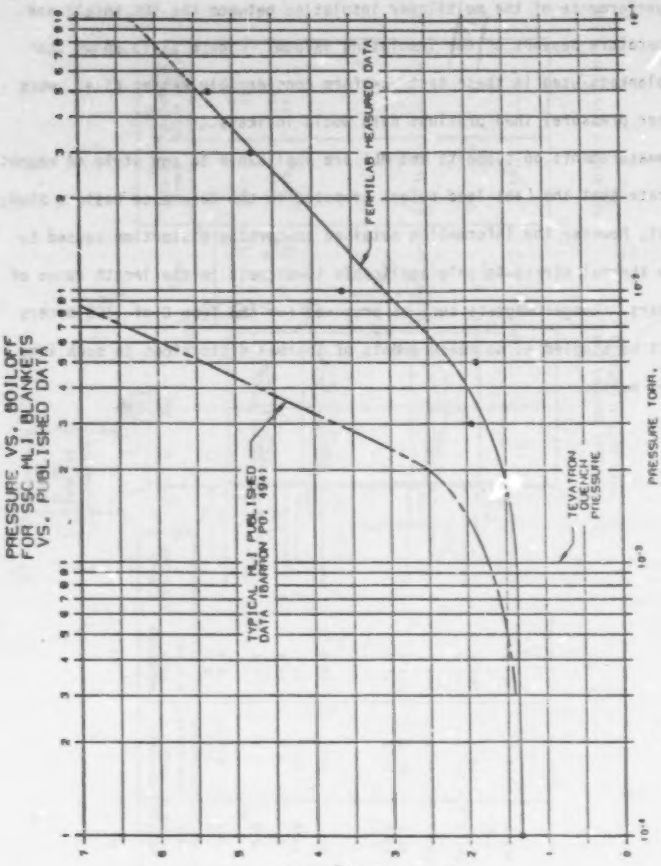


Fig. II.13 Performance of multilayer insulation vs. vacuum.

III. DESCRIPTION OF VARIOUS MAGNET SYSTEMS

III.A. Style D - A High Field 1-in-1 Cold Iron Magnet

This section summarizes the 1-in-1 collared dipole design for SSC Reference Design D, a collaborative effort of BNL, LBL, and FNAL (Ref. 18).

Overall Design. The dipole is a cold iron (and cold bore), 1-in-1 magnet of 16.6 m magnetic length, utilizing a two-layer cosine theta coil of 4.0 cm aperture (coil i.d.). It is designed for an operating field in the range 6.0-6.5 T. (The SSC ring circumference corresponding to a guide field of 6.5 T is 90 km, and the number of dipoles in Reference Design D is approximately 8000.) The design operating temperature is 4.5K, obtained with forced circulation of high pressure supercritical (single phase) helium; the cryogenic system encompasses 12 refrigerators equally spaced around the ring and periodic re-coolers within each cryogenic loop. At this time only a conceptual design exists for the regular quadrupoles for this machine option: a one-layer coil with an inner diameter matching that of the outer layer in the dipole and utilizing the same conductor. It would have a cold-iron yoke without collars, a magnetic length of about 6.6 m, and a maximum gradient of about 140 T/m matched to 6.5 T in the dipole. Design D calls for approximately 1500 quadrupoles in the regular arcs.

Bore Tube Assembly. The high vacuum chamber, or cold bore tube, is a stainless steel tube of 3.3 cm i.d., copper coated on the inside to minimize the electrical resistance of the wall to image currents. On the outside of the bore tube are mounted superconducting sextupole and decapole correction coils. Several prototype designs well suited for mass production are under development. Between these and the main dipole coil are longitudinal plastic insulator-spacer strips spaced to furnish annular helium cooling passages.

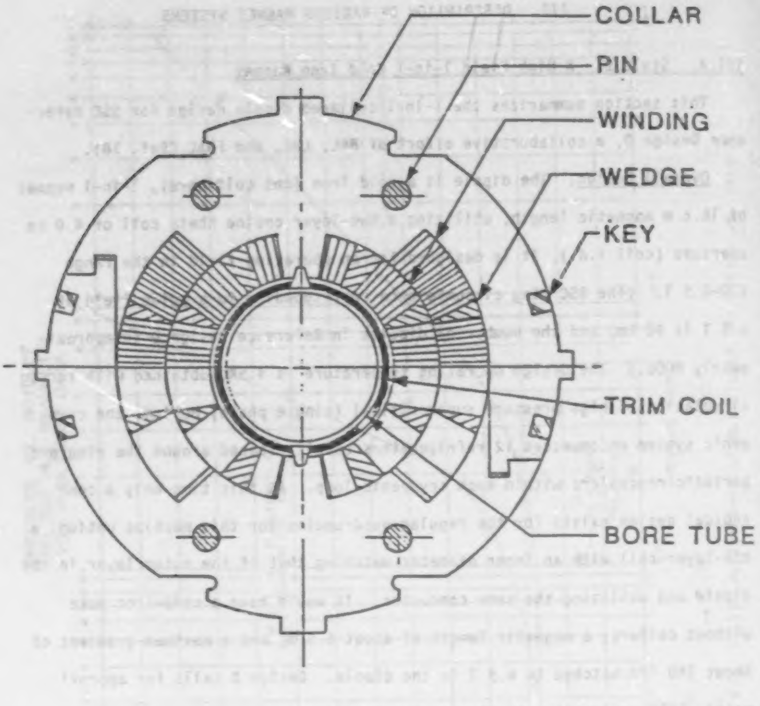

COLLAR
PIN
WINDING
WEDGE
KEY
TRIM COIL
BORE TUBE

Fig. III.1 Cos θ style collared coil.

Coil. The collared coil subassembly is shown in Fig. III.1. Both coil layers are wound from partially keystoned (about 1.8 degree) flat "high homogeneity" NbTi cable of the Rutherford type. Mechanical stability and optimal conductor placement in the completed coil package are achieved by inclusion of copper wedges in the coil cross section. Since the field in the outer coil is lower, the cable is graded according to current density, with the inner layer (16 turns) wound from a 23-strand cable of Cu:SC ratio 1.3:1 and the outer layer (20 turns) from a 30-strand cable (1.8:1). The two layers are powered in series, with approximately 6 kA corresponding to a central field of 6 T. The cable insulation consists of a double wrap of Kapton followed by one layer of fiber glass impregnated with B-stage epoxy; the latter serves to hold the coil together during handling. (A possible coil fabrication procedure without fiber glass epoxy is also being studied.) The individual coil sections are wound under computer control on a precision laminated convex mandrel, and subsequently epoxy-cured in a laminated concave fixture under pressure. During assembly additional insulation is introduced: Kapton on the mid-plane and Kapton and Teflon (the latter serving as a slip plane) between coil layers. The coil ends are flared out from a minimum i.d. in the straight section of 4.0 cm to about 8.9 cm. An advantage of this feature is a reduction of the peak end field associated with straight saddle coils without resorting to the usual spacers between end turns. Recent experiments have indicated that a flared end is not needed for NbTi conductor and if further development confirms this finding, then straight ends, as used in the Tevatron, would become standard.

Collars. The coils are compressed with 1.5 cm wide collars of fully austenitic, non-magnetic stainless steel pre-assembled in packs from 1.5 mm thick laminations. The collars simplify subsequent assembly in the iron yoke and provide the necessary restraint to maintain the coil under a compressive stress of about 6 kpsi. The relatively thin radial width minimizes the loss in contribution to the magnetic field from the yoke (a loss of about 0.2 T in B_o at high field); conversely, a benefit from collars is a sharp decrease in the effect of iron saturation on the allowed harmonics (a shift less than one 2×10^{-4} for b_2 in the present design). The coils are insulated from the collars with several layers of Kapton sheet.

Cooling Scheme. The high pressure (4 atm) supercritical helium flows through the annular space between the trim coils and the main coil (where part of the heat load intercepted is due to synchrotron radiation), through passages between the collars and yoke, and through larger channels in the yoke. The bulk of the helium mass flow, 100 g/sec, flows through the yoke bypass channels; about 1 g/sec is needed in the coil region to act as a transfer medium for heat from the bore tube.

Yoke and Cryostat. The yoke, 26.67 cm (10.5 in.) in o.d., is assembled from modular blocks fabricated from laminations of low carbon steel, mounted in the helium containment shell as in Fig. III.2. The laminations are punched with keyways for accurately locating the collared coil assembly within the yoke. The two large rectangular slots carry the main and diode bypass electrical bus (top) and correction element leads (bottom). The four large holes are the channels for helium flow; the smaller holes near 40 degrees are for tensioned alignment rods. The tolerances on yoke length and weight are met with the aid of a select number of filler laminations and proper compression of the lamination stack. The helium vessel is fabricated from stainless steel half shells, welded shut on the mid-plane with the top and bottom subassemblies held in contact under pressure. Holes are provided in the containment shells for the insertion of fiducial marking plugs into recessed slots in

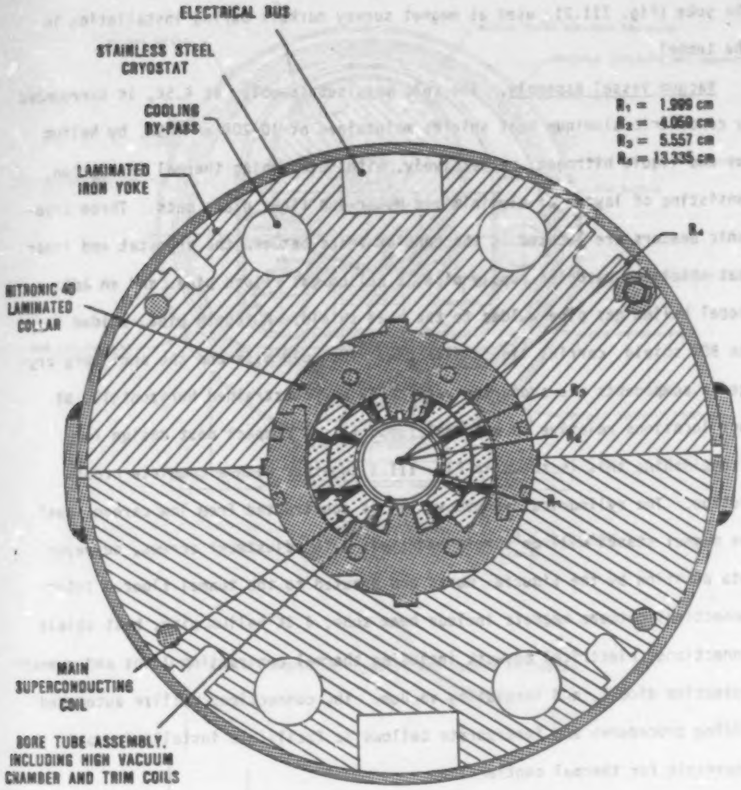

ELECTRICAL BUS
STAINLESS STEEL CRYOSTAT
COOLING BY-PASS
LAMINATED IRON YOKE
NITRONIC 40 LAMINATED COLLAR
MAIN SUPERCONDUCTING COIL
BORE TUBE ASSEMBLY, INCLUDING HIGH VACUUM CHAMBER AND TRIM COILS
R_1 = 1.999 cm
R_2 = 4.050 cm
R_3 = 5.557 cm
R_4 = 13.335 cm
R_4
R_3
R_2
R_1

Fig. III.2 Completed helium containment cross section.

the yoke (Fig. III.2), used as magnet survey markers during installation in the tunnel.

Vacuum Vessel Assembly. The cold mass subassembly, at 4.5K, is surrounded by concentric aluminum heat shields maintained at 10-20K and 80K, by helium gas and liquid nitrogen, respectively, with intervening thermal insulation consisting of layers of aluminimized Mylar and fiber glass mats. Three cryogenic headers are located in the annular space between the cryostat and inner heat shield: a recooler supply pipe, a helium gas return pipe, and an additional helium gas pipe welded to the heat shield. A fourth pipe, welded to the 80K shield, carries liquid nitrogen. The cold mass and the ancillary cryogenic components are supported vertically and constrained horizontally at four locations relative to external supports. A compact post design for accomplishing this is shown in Fig. III.3 together with a complete cross section. The cylindrical vacuum vessel is constructed from low carbon steel. The magnet stands will be simple pedestals with adjustment screws, surveyed into position by the fiducial marks and grouted to the tunnel floor. Interconnections between magnets include beam tube, 4.5K helium pipe, heat shield connections, electrical buswork including thermal contraction loops and quench-protection diodes, and insulating vacuum. The connections utilize automated welding procedures and incorporate bellows to facilitate installation and compensate for thermal contraction.

III.B. Style B - The Ironless Cosine θ Option For The SSC

The most prominent and distinguishing features of Reference Design B are its particular style of magnet. Separate cryostats are used for each of the two collider rings, arranged one above the other. The magnet is proposed as 5.5 T, 1-in-1 design, using warm shielding iron located far from the coils. The dipole length is 12 m and the mechanical aperture of the coil is 5 cm.

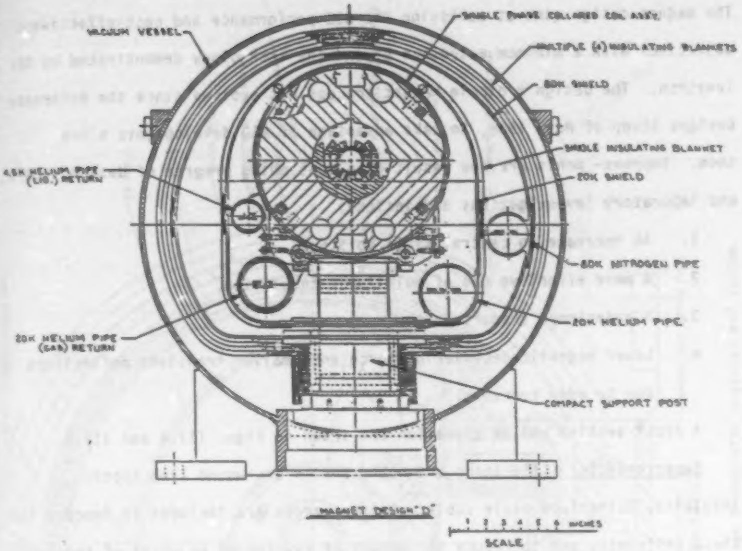

VACUUM VESSEL
SINGLE PHASE COLLARED COIL ASS'Y
MULTIPLE (4) INSULATING BLANKETS
80K SHIELD
SINGLE INSULATING BLANKET
4.5K HELIUM PIPE (LIQ.) RETURN
20K SHIELD
80K NITROGEN PIPE
20K HELIUM PIPE
20K HELIUM PIPE (GAS) RETURN
COMPACT SUPPORT POST
MAGNET DESIGN "D"
0 1 2 3 4 5 6 INCHES
SCALE

Fig. III.3 Completed cryostat and vacuum enclosure.

The magnet design aims at achieving the SSC performance and cost-effectivene objectives with a minimum extension beyond the technology demonstrated by th Tevatron. The design B dipole magnet concept has evolved since the Reference Designs Study of May, 1984, to take advantage of R&D developments since then. Improve- ments are the result of a continuing program of design studies and laboratory investigations and include:

1. An increase in central field to 5.5 T.
2. A more effective use of multilayer insulation.
3. A redesigned support post.
4. Lower magnetic decentering force and smaller transient deflections due to eddy currents.

A cross section and an elevation are shown in Figs. III.4 and III.5.

Superconductor. The inner and outer shells are wound from Kapton-insulated, Rutherford-style cable. Copper wedges are included to improve the field uniformity and to reduce the amount of keystoning required of the cable. Winding parameters are listed below:

	Inner	Outer
Number of turns	25	18.5
Number of strands in cable	25	23 (both use 0.76 mm strand)
Copper to superconductor ratio	1.8	2.5

The design has assumed that superconducting strand will be available with critical current density of 2500 A/mm^2 at 5 T and 4.2K.

Collared Coil Assembly. The Kapton-insulated cable is dry wound onto a collapsible mandrel in one complete operation. The aluminum collars are installed, closed incrementally, and keyed together as the mandrel is withdrawn. A 3-mm thick stainless shell installed over the collars completes

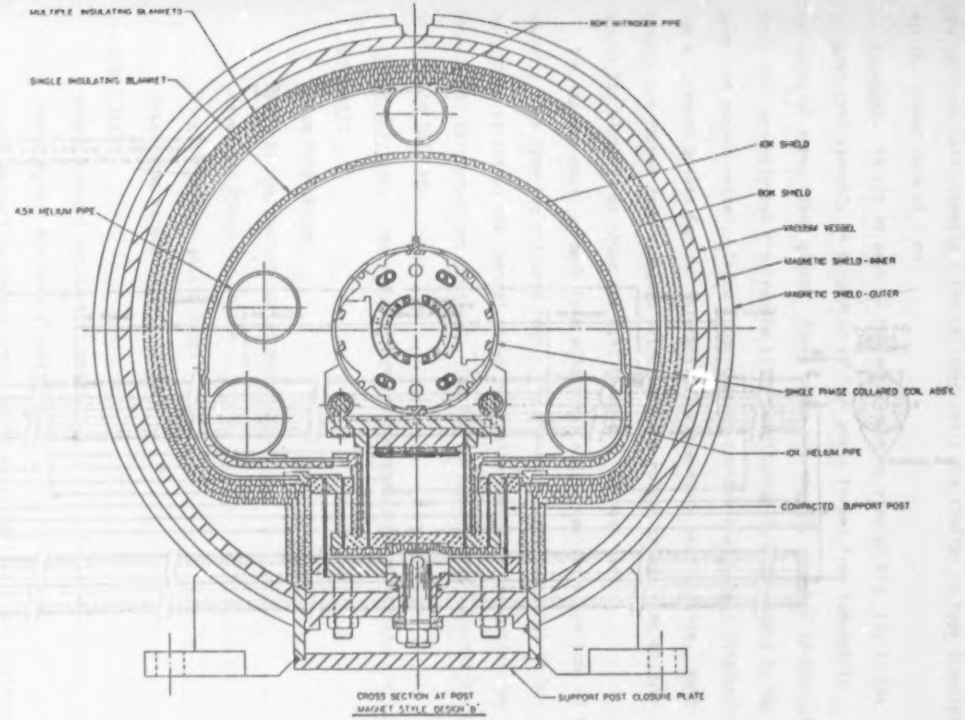
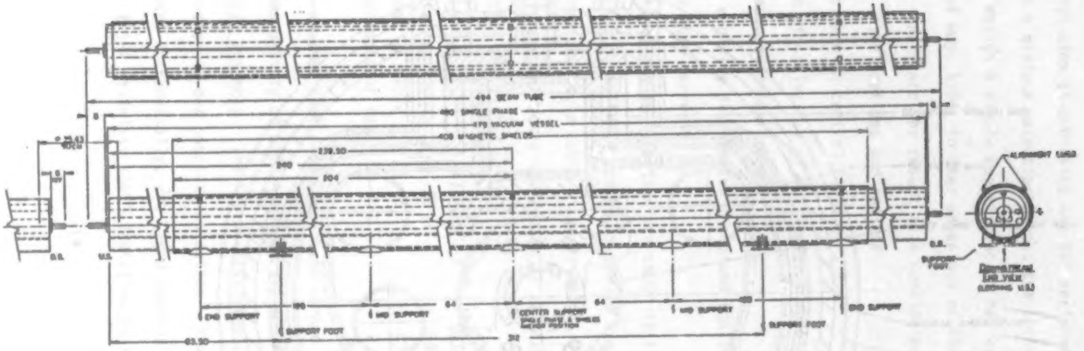

MULTIPLE INSULATING BLANKETS
80K NITROGEN PIPE
SINGLE INSULATING BLANKET
10K SHIELD
80K SHIELD
4.5K HELIUM PIPE
VACUUM VESSEL
MAGNETIC SHIELD-INNER
MAGNETIC SHIELD-OUTER
SINGLE PHASE COLLARED COIL ASSY.
10K HELIUM PIPE
COMPACTED SUPPORT POST
CROSS SECTION AT POST
MAGNET STYLE DESIGN 'B'
SUPPORT POST CLOSURE PLATE

Fig. III.4 Design B completed cryostat and vacuum.


494 BEAM TUBE
480 SINGLE PHASE
470 VACUUM VESSEL
408 MAGNETIC SHIELDS
238.50
240
204
B
U.S.
D.S.
120
64
64
120
℄ END SUPPORT
℄ MID SUPPORT
℄ CENTER SUPPORT SINGLE PHASE & SHIELD ANCHOR POSITION
℄ SUPPORT FOOT
SUPPORT FOOT
312
83.50
ALIGNMENT LUGS
DOWNSTREAM END VIEW (LOOKING U.S.)

NOTES:
1 B DISTANCE BETWEEN ENDS OF EFFECTIVE FIELDS.
2 SEE SHEET 2 of 3 FOR TYP CROSS-SECTION.
3 SEE SHEET 3 of 3 FOR CROSS-SECTION THRU POST.

Fig. III.5 Magnet style B.

the collared coil assembly. The collared coils are similar to type D except for the larger bore of 5 cm.

Cryostat. As can be seen in the cross-section view of Fig. III.4, the collared coil assembly is supported at four posts formed from concentric cylinders of epoxy fiber glass. These posts are rigidly attached to the collared coil assembly but are free to slide longitudinally with regard to the warm iron vacuum vessel. These support posts provide the thermal intercepts and attachment points for two intermediate temperature heat shields. Both shields are formed from aluminum extrusions and rolled shapes. Multilayer insulation blankets as shown are used to reduce the heat leak.

The vacuum vessel is made from mild steel and serves to return some of the magnetic flux from the collared coil. Its dimensions are such that it has negligible effect on the central field and neither magnetic properties nor dimensional tolerances are critical. The R&D to support this cryostat design is given in Ref. 16.

Interconnections. The required interconnections between magnets are:

Cryogenic

- beam tube vacuum
- main helium coolant containment tube
- cryogenic lines for helium
- liquid nitrogen shield lines
- insulating vacuum

Electrical

- magnet current bus bars (1 pair)
- quench bypass bus bars (1 pair)
- quench protection diodes installed in every half cell and instrumentation leads, quench detection voltage taps, and correction coil leads.

To obtain the most reliable leak tight connections all internal fluid connections are welded stainless-steel joints made by automatic welding equipment. Joints in the beam tube that separate the single phase helium flow from the beam vacuum are made with double wall bellows having an intermediate space for leak interception. Electrical connections are made within the feedthroughs except where necessary at the quench heaters. Connections are supported by insulating bars and junction boards. Expansion joints are provided in the bus to accommodate thermal expansion which is of the order of an inch.

Quadrupole. The quadrupole coil uses the same conductor specified for the dipole; the inner coil has 8 turns and the outer has 14. At a current of 6600 A (5.5 T in the dipole) the quadrupole has a gradient of 154 T/m. Except for its shorter length, the quadrupole cryostat is essentially the same as the dipole cryostat.

Correction Coils. Persistent currents flowing within the superconductor during magnet excitation give rise to a current dependence in the sextupole and decapole moments for all cosine theta superconducting dipole designs. By using conductor with a filament size of less than 3 μm, persistent current induced multipoles may be small enough to permit the corrections to be made by the usual relatively short correction magnets located near the quadrupoles. If small filaments cannot be made satisfactorily, it is necessary to correct locally these unwanted field components to obtain reasonable magnetic aperture for injection and acceleration of the beam. A model of this effect has been developed and tested with current-dependent data obtained from Tevatron dipoles (Ref. 17). Alternatively, bore tube mounted correction windings applicable to all high field magnets styles are being developed (see Style D) and could be used.

III.C. Style A' - The High Field 2-in-1 Coil Iron Design

Style A' incorporates 2 collared coils of the Style D design in a single yoke and cryostat to form a 2-in-1 magnet with horizontally aligned bores. The only significant difference between the dipoles of type D and A' is the 2-in-1 yoke in the latter design (Ref. 20). As a consequence of the assumed identical collared coils, the performance characteristics of the two magnets, e.g., peak field, transfer function etc., are about the same. The systematic multipoles in style A' are approximately the same as for style D. An overall cross section of the A' cold mass is shown in Fig. III.6. The cryostat concept shown in this figure illustrates a ring girder support system that is different than the pedestal supports shown for styles A and B, and is shown in this figure to illustrate a slightly different cryostat concept. Here the yoke o.d. is 35.56 cm (14 in.), with center-to-center separation between the two apertures of 16.51 cm (6.5 in.), determined primarily by the minimum practical separation between the collared coils in the flared ends, and the minimum allowable thickness of the outer return leg in the yoke. (In this particular design, the return leg is heavily saturated at full field, with twice as much flux crossing from one aperture to the other as is returned through the outer leg.)

The two cut-outs on the vertical center line at either pole are for accommodating heavy strong backs; the four rectangular slots at 40 degrees from the horizontal axis are for the electrical bus. The two large holes on the vertical center line replace the four helium bypass channels in Design D. In a 2-in-1 dipole, the quadrupole harmonic is an allowed term in the absence of left-right symmetry; the magnitude of this term was minimized by adjusting the size and location of the two bypass holes.

III. ANALYTICAL RESULT OF TUNE SHIFTS

One of the criteria for linear aperture concerns the tune shifts (section 2.1). The program MARYLIE has been used to evaluate the tune shifts as functions of the horizontal and vertical emittances ϵ_x and ϵ_y as well as functions of the fractional energy error δ (Etienne Forest). The program takes account of nonlinearities up to the octupole order. In this effort, random multipoles up to a_3 and b_3 are included. A third-order map is then generated by MARYLIE for the entire storage ring. The tune shifts are given by the expressions:

$$\Delta\nu_x = -(4\ a\ \epsilon_x + 2\ b\ \epsilon_y)/2\pi + d_x\ \delta^2/2 \qquad (11)$$

$$\Delta\nu_y = -(2\ b\ \epsilon_x + 4\ c\ \epsilon_y)/2\pi + d_y\ \delta^2/2.$$

The map generated is used to extract the coefficients a, b, c, d_x and d_y. Table 3 gives the results. The tune shifts are of the order of $(\text{sextupole})^2$ and (octupole).[1] This is in contrast with the smear which is a first order effect of the sextupole strengths.

The tune shifts in the linear aperture criterion are interpreted as the tune shift contributions due to the magnet field multipole errors. The contributions from the bare lattice without field errors are thus subtracted out in the tune shifts before applying the criterion. If desired, the tune shifts of the bare lattice can in principle be reduced by applying a more sophisticated sextupole scheme.

The linear aperture according to the tune shift criterion (ignoring the smear criterion) is then given by

$$A_{\text{linear}} = (2\ \beta_{\max}\ \epsilon_{\text{linear}})^{1/2} \qquad (12)$$

the values of linear aperture determined according to the tune shift criterion

Table 3. Coefficients appearing in Eq.(11) for the C1, C1S, D1 and D1S Lattices. (The three sets of results for C1 represent sampling over three sets of random errors. The third set does not have the corrasponding sorted result.)

lattice	a/1000	b/1000	c/1000	$d_x/1000$	$d_y/1000$	A_{linear}
C1 no errors	3.2	28	1.8	-3.1	-3.2	
C1 with errors						
- without sorting	118	-514	35	-30	13	5.4 mm
- with sorting	111	-443	50	-32	14	5.6
- without sorting	60	-517	211	-51	53	5.4
- with sorting	52	-457	215	-51	54	5.7
- without sorting	-57	133	-34	-9	15	11.5
C1S no errors	41	331	24	-2.9	2.8	
C1S with errors						
- without sorting	52	316	15	-3.3	-2.7	19
- with sorting	52	323	17	-3.2	-2.8	19
D1 no errors	2.8	25	1.5	-2.1	-2.3	
D1 with errors						
- without sorting	2.7	11	9	6.1	-6.6	27
- with sorting	15	14	1.0	3.2	-8.6	21
D1S no errors	42	400	12.3	-2.8	-2.8	
D1S with errors						
- without sorting	47	386	15	-3.0	-2.8	20
- with sorting	45	389	12	-2.8	-2.7	22

where β_{max} is the maximum β-function in the cells and ϵ_{linear} is determined by

$$0.005 = |4a - 4a_o| \, \epsilon_{linear}/2\pi$$

$$0.005 = |2b - 2b_o| \, \epsilon_{linear}/2\pi \quad \text{whichever is reached first}$$

$$0.005 = |4c - 4c_o| \, \epsilon_{linear}/2\pi \qquad (13)$$

where a_o, b_o and c_o refer to values for the bare lattices since we intend to include only the tune shift contributions from the magnet field errors. The values of A_{linear} are listed also in Table 3. As we will see,

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they are not as stringent as those determined according to the smear criterion. We will therefore not be discussing the tune shift criterion until section 5.1.

Note that the short cell bare lattices have larger tune shifts (see the b coefficients in Table 3) than the long cell cases. This is due to the higher strengths of the chromaticity sextupoles. The relatively large tune shifts for C1 with errors is partially due to statistics and partially due to the larger β-functions.

Table 3 also gives the result when sorting is included. It is noted that the sorting scheme used did not improve significantly the tune shifts. On the other hand, as we will see later, sorting does improve the smear.

IV. RESULTS OF SIMPLE TRACKING WITH FODO CELLS

4.1 The Model

Anticipating that the sextupole and skew sextupole field errors dominate the determination of the linear aperture in the neighborhood of interest, the smear is expected to behave according to

$$\text{smear} \propto \beta\,(a_2 \text{ or } b_2)A, \tag{14}$$

where β is the typical β-function in the cells, A is the betatron amplitude being considered. Since $\beta \propto L$ and $(a_2, b_2) \propto d_c^{-5/2}$, we expect

$$\text{smear} \propto L\, d_c^{-5/2}\, A. \tag{15}$$

A simple tracking method is devised (Don Edwards, Norman Gelfand, Tom Collins) to quickly obtain the linear aperture in the multi-dimensional variable space of interest. The smear results are obtained for various combination of L, d_c, A and random number seeds. Guided by the expected behavior, an effort is made to fit these results using the form of Eq.(15) except that the power in A is left free, i.e.

$$\text{smear} = L^{1.0}\, d_c^{-2.5}\, A^{\eta}, \tag{16}$$

with and η free fitting parameters (η is expected to be close to 1). The accuracy of results obtained is spot checked against the more elaborate trackings (Chapter V). Both the model and the checking will be improved as the study proceeds.

In this effort, the FODO lattice (section 2.3) is used. The betatron phase advance per cell is slightly changed from exact 60° so that the tunes are given by $\nu_x = 80.185$, $\nu_y = 80.195$. Thin lens quadrupoles are used. A reference point is defined to have L = 107 m, d_c = 4 cm. When d_c is varied, the multipole error coefficients a_n and b_n are varied according to Eq.(10). When L is varied, the quadrupole strength is changed to keep the phase advance per cell fixed. To speed up the calculations, the lattice is fixed to have 481 FODO cells as L is varied.

Tracking is performed to calculate the smear as a function of L, d_c and the amplitude $A = (A_x^2 + A_y^2)^{1/2}$. The smear obtained is then scaled to the correct number of cells, N_{cell}, by $(N_{cell}/481)^{1/2}$. (This scaling was checked numerically first for one case.)

The smear depends on the chosen random multipoles. In this study, a fixed set of magnets with random multipoles is chosen but the ordering of these magnets is varied, yielding a statistical distribution of smear for given L, d_c and A.

4.2 Tracking Results

The final results are collected to give

$$\text{smear} = \begin{cases} (0.0019 \pm 0.0006)\ [L(\text{m})]^{1.0}\ [d_c(\text{cm})]^{-2.5}\ [A(\text{mm})]^{1.39} & \text{for C design} \\ (0.0034 \pm 0.0011)\ [L(\text{m})]^{1.0}\ [d_c(\text{cm})]^{-2.5}\ [A(\text{mm})]^{1.32} & \text{for D design} \end{cases} \qquad (17)$$

The fitted values are given together with their rms statistical errors. The dependences on L and d_c are first checked to be consistent with the tracking results in the neighborhood of the reference point with L = 107 m and d_c = 4 cm. The relatively large error bars comes mainly from the statistics and to a less degree from the fitting form Eq.(16). The fit (17) is a good approximation in the neighborhood of the reference point; it deteriorates especially for short cell length because then the chromaticity sextupoles begin to play an important role. Equation (17), which ignores the chromaticity sextupoles in its dependence on L, will predict a smaller smear than the actual case. This we will discuss more in section 5.1. However, in regions of interest, Eq.(17) gives the scaling reasonably accurately.

For fixed d_c and L, the smear increases as A is increased. As the smear reaches the level of 10%, the linear aperture A_{linear} is reached. Setting smear=10% in Eq.(17) gives the achieved linear aperture

$$A_{linear}(mm) = (17\pm4)\ [L(m)]^{-0.719}\ [d_c(cm)]^{1.80} \text{ for C design} \qquad (18)$$

$$= (13\pm3)\ [L(m)]^{-0.757}\ [d_c(cm)]^{1.894} \text{ for D design.}$$

Figures 6 and 7 give the achieved linear aperture (the mean values without error bars) in the (d_c, L) plane for the C and D designs.

The achieved linear aperture needs to be equal or larger than the needed aperture. Substituting the needed linear aperture, Eq.(2), in Eq.(18) gives the relationship between d_c and L that the linear aperture requirement imposes on the choice of these two parameters

$$d_c(cm) = (0.20 \pm 0.03)\ [L(m)]^{0.60} \text{ for C design} \qquad (19)$$

$$= (0.25 \pm 0.03)\ [L(m)]^{0.59} \text{ for D design.}$$

These results are plotted in Fig. 8. The two curves represent the trade-off between d_c and L for the C and the D magnet designs. As far as the linear aperture is concerned, points along the curve are equivalent. Figure 8 is one of the main results of the present aperture study. Combined with the cost curves, Figs. 3 and 4, the aperture determination will be made in the conclusion (Chapter VII).

Smear is also a function of the observation point in the storage ring. The above results are obtained at a fixed location. The variation of smear at other locations is typically relatively small, as shown in Fig. 9. We ignore this variation.

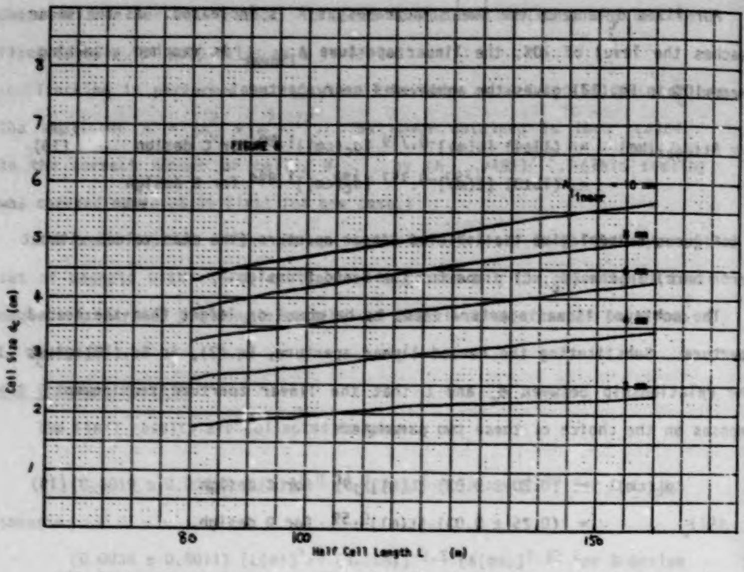

Fig.6. Contour plot of the achieved linear aperture in the (L, d_c) plane for the C magnet design.

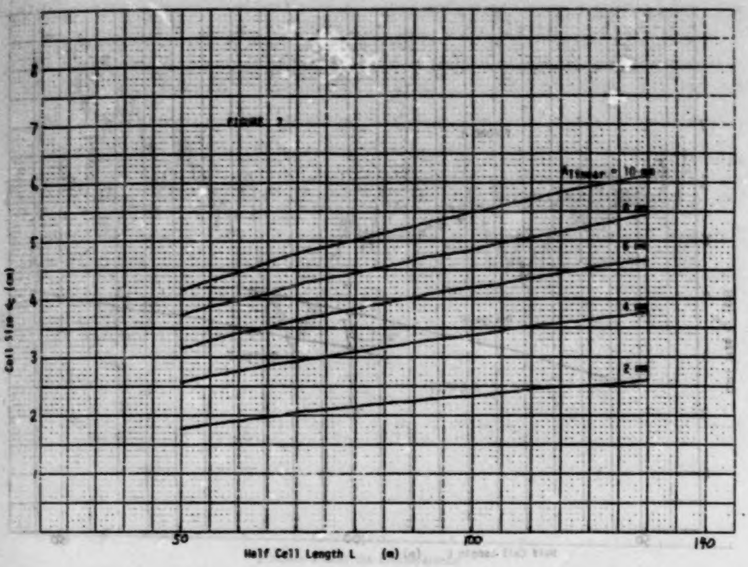

Fig.7. Same as Fig. 6 but for magnet Design D.

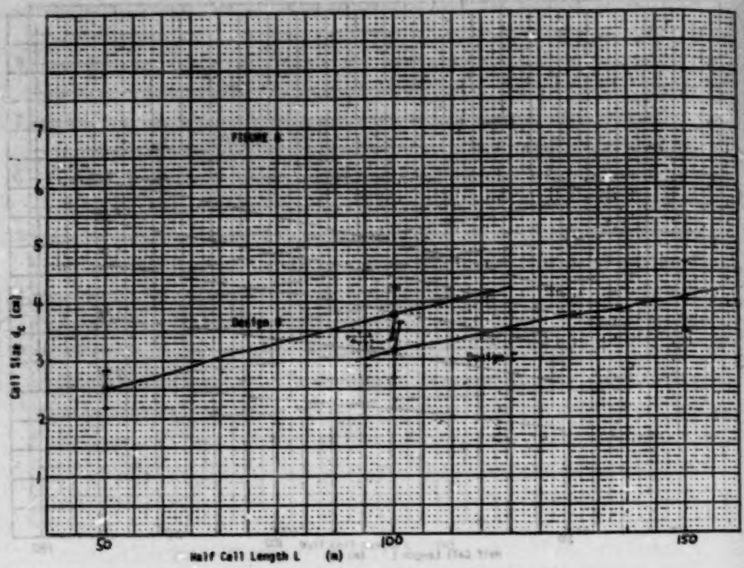

Fig. 8. The trade-off curves between cell length L and inner coil diameter d_c as far as achieving the needed linear aperture is concerned for magnet designs C and D.

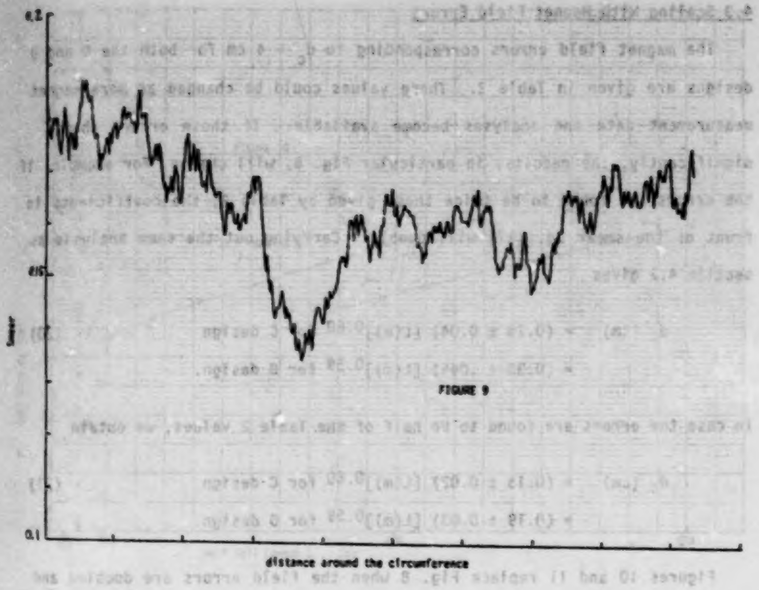

FIGURE 9

Fig. 9 Variation of smear as a function of the point of observation in the ring. A typical case is used.

4.3 Scaling With Magnet Field Errors

The magnet field errors corresponding to d_c = 4 cm for both the C and D designs are given in Table 2. These values could be changed as more magnet measurement data and analyses become available. If these errors change significantly, the results, in particular Fig. 8, will change. For example, if the errors are found to be twice those given by Table 2, the coefficients in front of the smear Eq. (17) will double. Carrying out the same analysis as section 4.2 gives

$$d_c\ (\mathrm{cm}) = (0.26 \pm 0.04)\ [L(\mathrm{m})]^{0.60} \text{ for C design} \tag{20}$$
$$= (0.33 \pm .045)\ [L(\mathrm{m})]^{0.59} \text{ for D design.}$$

In case the errors are found to be half of the Table 2 values, we obtain

$$d_c\ (\mathrm{cm}) = (0.15 \pm 0.02)\ [L(\mathrm{m})]^{0.60} \text{ for C design} \tag{21}$$
$$= (0.19 \pm 0.03)\ [L(\mathrm{m})]^{0.59} \text{ for D design.}$$

Figures 10 and 11 replace Fig. 8 when the field errors are doubled and halved, respectively.

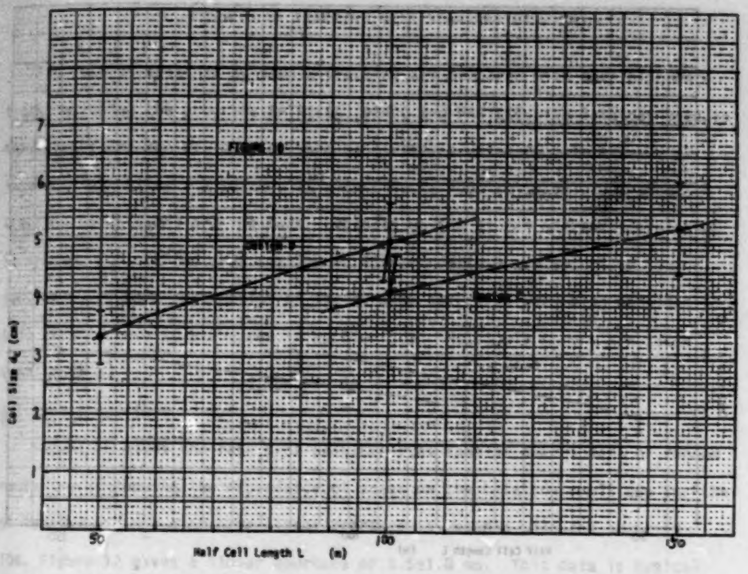

Fig. 10. To replace Fig. 8 if field errors are found to be double those given by Table 2.

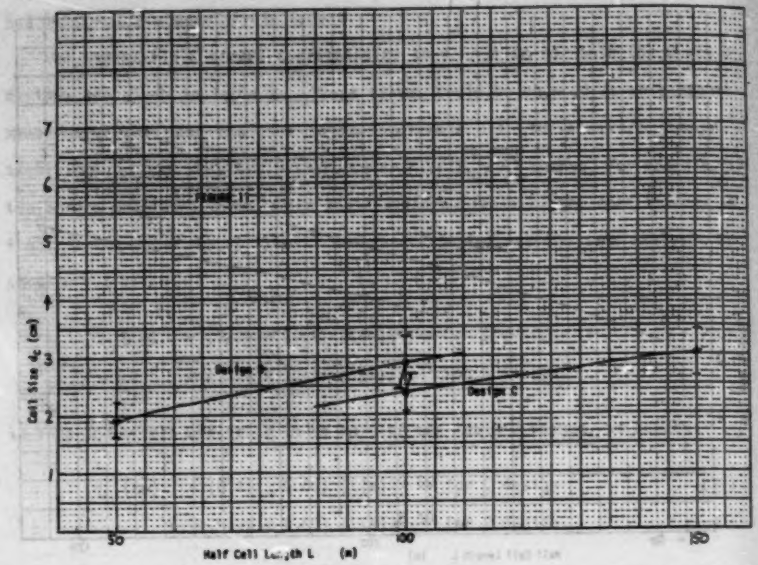

Fig. 11. To replace Fig. 8 if field errors are found to be half those given by Table 2.

V. RESULTS OF TRACKING WITH STANDARD PROGRAMS

The results obtained by simple tracking are compared with more elaborate trackings using the programs PATRICIA, DIMAD and MARYLIE. The lattices used in this effort are the C1, C1S, D1, and D1S lattices which contain the interaction regions. Also results with 6 Tesla FODO cells only but accurate tracking using DIMAD are included. Results on the linear apertures are given in section 5.1. Effects of sorting on linear aperture are described in section 5.2. Some information on the dynamic apertures were also obtained in this effort; results are given in section 5.3. Multipole errors are taken from Table 2.

5.1 Linear Aperture

Figure 12 gives the result of PATRICIA runs sampled over 5 sets of random number seeds showing the dependence of smear on the betatron amplitude for the D1 lattice and $d_c = 4$ cm. The linear aperture is reached when the smear is 10%. Figure 12 gives a linear aperture of 5.5±1.0 mm. This data is typical of the data of all programs discussed below.

Data appropriate for "luminosity lattices" having $B^* = 1$m are given in Fig. 13 and for "injection lattices" having detuned IR's or no IR's at all are given in Fig. 14.

Figure 13 gives the linear aperture achieved for a fixed coil diameter of $d_c = 4$ cm as a function of cell length for magnet design D. The curve, obtained from Eq.(18), represents the result obtained using the simple FODO tracking. Error bars are indicated at L= 50 and 100 m. As mentioned, it is expected that this result is accurate in the neighborhood of L = 100 m while it may be expected to overestimate the linear aperture when the chromaticity

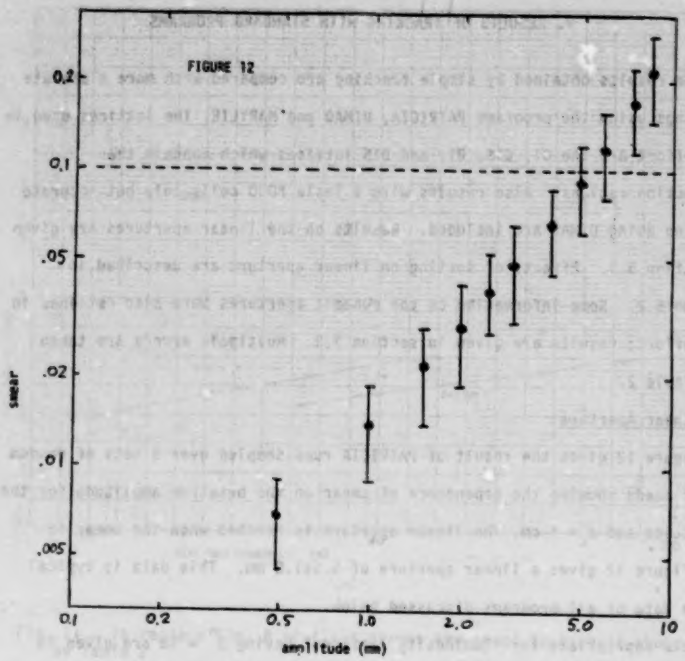

Fig. 12. Smear as a function of amplitude for D1 lattice as predicted by the program PATRICIA.

sextupoles begin to play a significant role, which is expected to occur when $L < 75$ m or so. (Note that the chromaticity sextupole strength $\propto L^{-3}$). This is represented by a drawing dashed curve in that region of Fig. 13..

The PATRICIA, DIMAD and MARYLIE results for "injection lattices" (Beat Leemann, Etienne Forest, Lindsay Schachinger, Steve Peggs), are shown in Fig. 14. These results basically confirm the expected behavior. Points are averages of, typically, several random seeds, with r.m.s.errors shown.

We made an attempt to check if indeed the chromaticity sextupoles (a) do not play an important role for $L = 100$ m, and (b) do play a role for $L = 50$ m and that, by somehow removing their effects, one obtains basically the result of Eq.(18). This behavior is strongly suggested by the DIMAD results with FODO cells only. For $L = 94$ m the linear aperture is increased by a factor of five when random errors are set to zero. For $L = 65$ m the increase in linear aperture is a factor of 2 when the random errors are set to zero.

To further confirm (a) we increased β^* from 1 m to 10 m, thus reducing the chromaticity sextupole strengths by roughly a factor of 2 (Steve Peggs, Al Garren). In Fig. 14 results from PATRICIA (one set of random numbers), DIMAD (five sets) and MARYLIE (five sets) are plotted along with the curve corresponding to Eq. (18). It is clear that the chromaticity sextupoles do not play an important role for $L = 100$ m.

To confirm (b), it is not enough to increase β^* since that would reduce the chromaticity sextupole strengths by only 30% or so. As shown in Fig. 14, the linear aperture obtained by MARYLIE is increased but only from 4.3 to 5.9 mm when β^* is increased from 1 to 10 m. However, by slightly splitting the phase advances per cell μ_x and μ_y while keeping the achromat principle on a superperiod basis, it is possible to reduce the chromaticity sextupole effects substantially. When this is done, MARYLIE gives a data

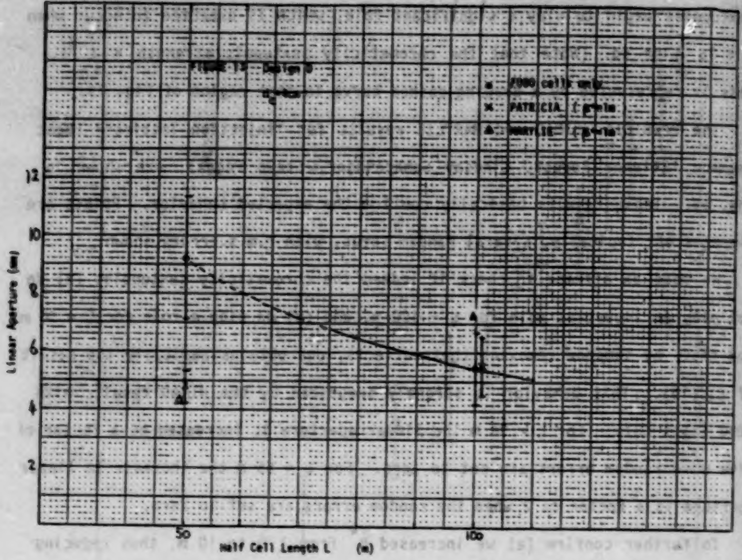

Fig. 13. Linear aperture as a function of L for design D "luminosity lattices" with d_c = 4 cm. The curve is from Eq.(18). Superimposed are tracking results from PATRICIA and MARYLIE. Equation (18) agrees with the elaborate tracking results for long cell lengths while overestimating the linear aperture for short cell lengths.

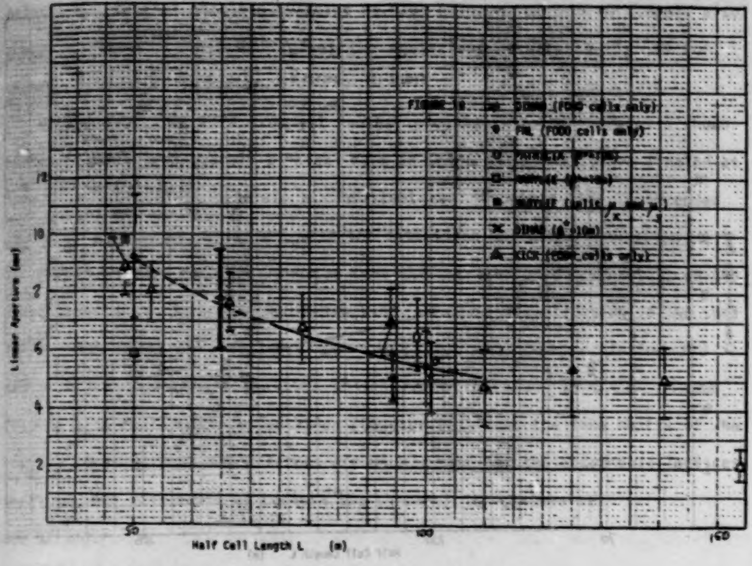

Fig. 14. Tracking results bearing on the aperture for "injection lattices" having detuned IR's. Design D.

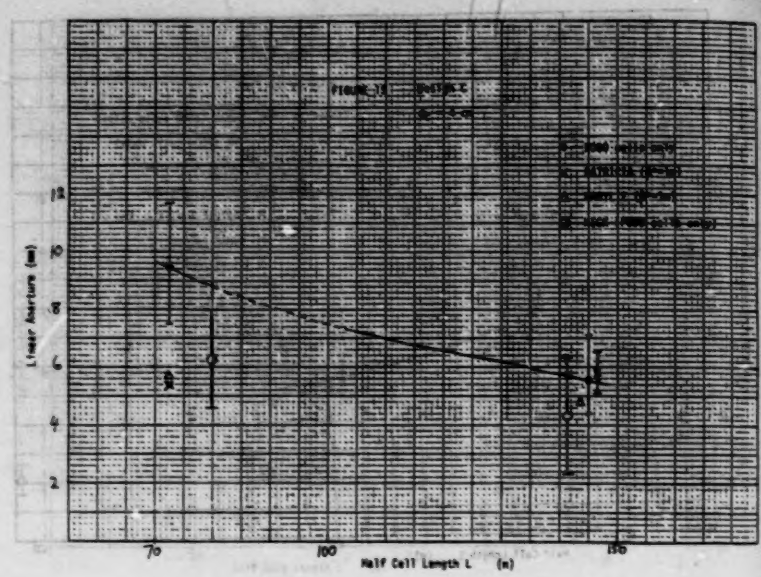

Fig. 15. The equivalent of Fig. 13 for Design C.

point close to that obtained by using Eq.(18) (linear aperture of 9.8mm), also shown in Fig. 14. Figure 15 gives the equivalent results as Fig. 13 for magnet design C at $d_c = 4$ cm.

Results labelled KICK from yet another program (R.Talman) are also shown in Fig. 14. This is purely a "kick" code in which all elements are treated as thin. It was used to generate a consistent set of points over an extended range. This data is consistent with the discussion which has been given.

So far we have been ignoring the tune shift criterion (section 2.1) on the linear aperture. During PATRICIA tracking, we have paid attention to the tune shifts with betatron amplitudes and found that the smear criterion is generally reached before the tune shifts reach the level of 0.005. These results also confirm the expectation (Chapter III) that the tune shifts of the bare lattices without field errors are much larger for the short cell lattices than the long cell lattices because the chromaticity sextupoles are stronger.

5.2 Effect of Sorting on Linear Aperture

The programs MARYLIE and DIMAD have been used to study the effects of sorting. (Etienne Forest and Lindsay Schachinger) The sorting scheme is that described in Fig. 2. The results of sorting on tune shifts have been described in Chapter III. It was found that the present sorting scheme did not change the tune shifts significantly. This is not the case as far as smear is concerned. Table 4 shows the linear aperture with and without sorting for the various cases studied using MARYLIE. Table 5 shows similar results using DIMAD with FODO cells only.

Table 4. Dependence of Linear Aperture on Sorting for Various Cases Studied using MARYLIE. Values for the Case of D1(β^*=10m) are Averaged Over Five Random Number Seeds. The sorting scheme used is that illustrated in Fig. 2.

Case	Without Sorting	With Sorting	Improvement factor
D1	7.3 mm	9.5 mm	1.30
D1S	4.3	4.6	1.07
C1	4.8	5.4	1.13
C1S	5.7	6.1	1.07
D1(β^*=10m)	6.5	8.8	1.35

Table 5. Dependence of Linear Aperture on Sorting for FODO Cells Only, Using DIMAD, and Averaging Over Five Random Number Seeds. The sorting scheme used is that illustrated in Fig. 2.

Case	Without Sorting	With Sorting	Improvement factor
94.3 m	5.1 ± 0.8	8.8 ± 2.3 mm	1.7
64.7 m	7.8 ± 1.7	9.6 ± 1.4	1.2

For the lattices with realistic IR's The effectiveness of sorting is most pronounced for the D1 lattices, giving typically a 30% improvement factor on the linear aperture. The improvement on D1S is less because the chromaticity sextupoles play a role as well as the random multipole errors. The improvement factor is also reduced for C1 because we have applied sorting on the b_2 errors only while the C design also has a sizable random a_2 error.

To apply our results (in particular the trade-off curves in Fig. 8 which contain error bars) later in Chapter VII, we will be taking the mean value along the curve. To be conservative, it might be thought advisable to take, for example, the upper end of the error bars. However, since even the rudimentary sorting improves the smear noticeably, we suggest taking the mean value without the conservatism. The studies are only indicative of the beneficial effects of sorting. If in the future a more effective sorting scheme with multiple variables is found, it is possible the coil diameter may be reduced further, but at present the mean value curves suffice.

5.3 Dynamic Aperture

The program PATRICIA has been used to find information on the dynamic aperture of lattices D1 and C1. In these runs, a dynamic aperture is identified to be the amplitude $A = (A_x^2 + A_y^2)^{1/2}$ beyond which the particle motion is unstable in less than 400 revolutions.

For the D1 lattice, the five sets of random multipole errors give the linear aperture of 6.5, 4.6, 4.9, 3.3 and 5.9 mm. The same sets of multipoles give dynamic apertures of 9.9, 9.4, 8.8, 8.4 and 9.4 mm, respectively. (Beat Leemann) Figure 16 shows the dynamic aperture (Fritz Dell) as a function of energy error δ for lattice C1. The on-momentum dynamic aperture for C design is about 9 mm. In both cases, the dynamic aperture is substantially greater than the linear aperture. The surplus aperture, as mentioned in Section 2.1, will be needed for various tuning purposes. Figure 16 shows an achieved momentum aperture of $\delta = \pm 0.15\%$. As will be discussed in Chapter VI, this seems just large enough to accommodate the needed energy spread of the beam against the single bunch transverse instability. Predictions of behavior at an amplitude as great as 1 cm in the C design have to be regarded as suspect since the mathematical convergence of the power series is clearly unsatisfactory there. This can be inferred from the coefficients of Table 2.

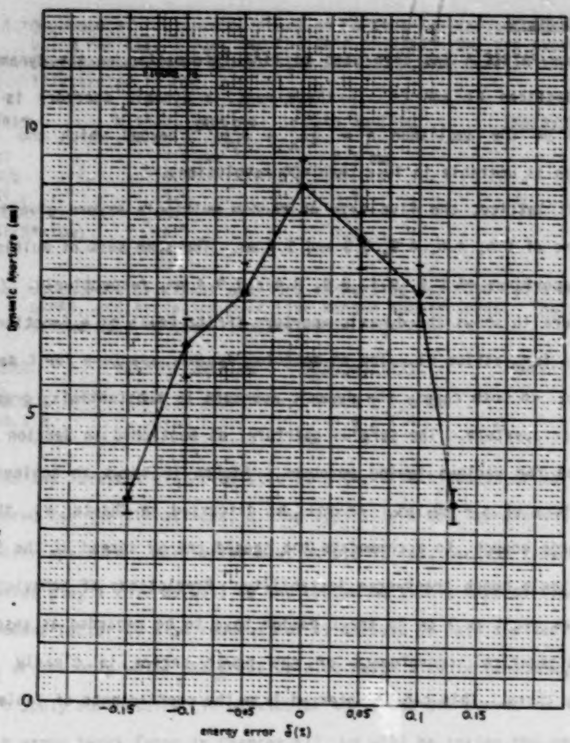

Fig. 16. Dynamic aperture vs. fractional energy error δ for Design C. Five sets of random numbers are used.

VI. COLLECTIVE EFFECTS

The physical aperture of magnets imposes a limit on the vacuum chamber size. The collective instabilities are driven by the longitudinal and transverse impedances, which becomes larger if the vacuum chamber size is small. When the physical aperture is determined, it is necessary to make sure that the vacuum chamber is large enough so that we are not operating beyond the threshold of collective instabilities. In this chapter, we give a conservative evaluation of the instability issue.

In this study (Joe Bisognano), we assume the same number of particles per bunch, $N_B = 1.5\times10^{10}$, the same bunch length, $\sigma_z = 7$ cm and the same injection energy E = 1 TeV for making the comparisons. The most important type of collective instabilty for the SSC is the transverse fast head-tail, or mode-coupling, instability. This instability can be stabilized if the beam has a sufficiently large energy spread σ_δ. However, a larger σ_δ requires a higher rf voltage and, more importantly, also requires a larger stable momentum aperture.

The threshold condition for the fast head-tail instability can be written as[7]

$$N_B = 45\ (E/e^2c)\ (R\ a/\beta Z_t)\ \sigma_\delta \qquad (22)$$

where a is the momentum compaction factor, β is the average beta-function at the impedances, Z_t is the characteristic transverse impedance, and R is the ring radius. The numerical factor of 45 in Eq.(22) is model dependent. The model used (gaussian bunch, no synchrotron and betatron tune spreads) is believed to give a somewhat lower threshold than a more realistic model but the scaling properties are valid.

The impedances are estimated for one high field and two low field cases. The parameters used are

case	B (tesla)	R (km)	L1/2(m)	b (mm)	μ	β(m)	α
1	3	28	145	33	60°	307	1.13×10^{-4}
					90°	242	5.34×10^{-5}
2	3	28	145	25	60°	307	1.13×10^{-4}
					90°	242	5.34×10^{-5}
3	6	15	100	33	60°	212	1.78×10^{-4}
					90°	167	9.0×10^{-5}

where b is the radius of the vacuum chamber pipe which is assumed round. Each case has two values of phase advance per cell μ. Case 2 is the same as 1 except for it has a smaller b to accommodate a smaller gap size of the superferric magnet design.

To illustrate how the impedances are estimated, we will describe the procedure for case 3 and then give the results for the other cases in a later table. For the SSC, the main contributions to the broad-band transverse and longitudinal impedances come from the bellows and the pick-up electrodes. With fractional contraction of 0.004 and allowing bellows to shorten by 1/3 of their lengths, 1.2% of the ring will be bellows. If unshielded, these bellows will exhibit a characteristic longitudinal impedance of $Z/n = 1.2\Omega$ and transverse impedance of $Z_t = 135\ \mathrm{M}\Omega/\mathrm{m}$. Since the bellows constitute the largest impedance, they will have to be shielded. To estimate the impedance of shielded bellows, we take the following conservative method: we begin with the impedance measured at PETRA and the expected impedance other than the shielded bellows. The difference is then interpreted as the contribution from the shielded bellows. The result of this exercise is that impedances of the SSC shielded bellows are $Z/n = 0.17\Omega$ and $Z_t = 20\mathrm{M}\Omega/\mathrm{m}$, a reduction by a factor of 7 due to shielding.

For the pick-up electrodes, we assume the strip-line design used in the Tevatron. We also assume one horizontal and one vertical electrode are placed near each quadrupole magnet. The estimated impedances are $Z/n = 0.08\Omega$ and $Z_t = 10\ M\Omega/m$.

Other sources of impedance are the resistive wall of cold copper, the rf cavities, the warm bore abort sections, the abort and injection kickers, and the miscellaneous discontinuities. The estimated impedances for these sources are $Z/n = 0.1\Omega$ and $Z_t = 20\ M\Omega/m$.

The following table gives the itemized impedance contributions for the three cases mentioned before. The two values for each entry represent the values of Z/n and Z_t respectively in units of Ω and $M\Omega/m$.

case	shielded bellows	pick-ups	others	total
1	0.17/37	0.055/13	0.053/20	0.28/70
2	0.23/85	0.055/23	0.053/20	0.34/128
3	0.17/20	0.08 /10	0.10 /20	0.35/50

In the above table, the bellow contributions are scaled with the ring radius R and the bore radius b according to $Z/n \propto 1/b$ and $Z_t \propto R/b^3$. The pick-up impedance is scaled by $Z/n \propto 1/L$ and $Z_t \propto R/Lb^2$, assuming there is a set of electrodes near each quadrupole magnet. For the other impedances due to kickers and warm bores, we assume that Z_t is independent of L and b, while $Z/n \propto 1/R$.

The transverse impedance is substituted in Eq.(22) to give the minimum beam energy spread σ_δ needed to stablize the beam against the single bunch fast head-tail instability. This yields the following results

	low field		low field (small bore)		high field	
case	1 (60°)	1 (90°)	2 (60°)	2 (90°)	3 (60°)	3 (90°)
needed $\sigma_\delta(10^{-3})$	0.11	0.18	0.20	0.33	0.063	0.10
needed acceptance $\pm\ 4\sigma_\delta(10^{-3})$	±0.44	±0.72	±0.80	±1.32	±0.25	±0.40

The energy acceptance of the ring optics should be $\pm 4\sigma_\delta$ to allow for a 3:1 bucket to bunch area ratio which is considered to be needed to avoid the damaging effects due to rf noise. The needed acceptance is also given in the above table. The energy acceptance needed for the low field case with small bore radius is beginning to have an impact on the momentum aperture, remembering the achieved momentum aperture for C1 lattice is $\pm 1.5\text{x}10^{-3}$ as shown in Fig. 16. Although the approach taken in this study is believed to be on the conservative side, indications are that the low field design will require a larger momentum aperture and that, if the small bore low field case is chosen, we will be operating with reduced safety margin.

VII. CONCLUSIONS

By overlaying the trade-off curve between d_c and L (Fig. 8) on the cost curves (Fig. 3 for Design C and Fig. 4 for Design D), one sees the optimum is rather broad with central values given by

$$d_c = 3.6 \text{ cm}, \ L = 155 \text{ m} \quad \text{for design C} \qquad (23)$$
$$d_c = 3.7 \text{ cm}, \ L = 95 \text{ m} \quad \text{for design D.}$$

Thus the cost estimating task force has taken $d_c = 4$ cm in the cost analyses.[7] Several points need to be discussed:

(a) The optimum parameters, Eq.(23), are very close to the ROS parameters $d_c = 4$ cm and L = 150 m for C and 100 m for D. Note, however, that the optimum is quite shallow. Very similar linear aperture and cost are obtained at any point along the trade-off curves (Fig. 8) in the range of L = 140-165 m for the C design and 85-105 m for the D design.

(b) From Eq.(23) and the cost curves, we obtain the cost per meter of bend for each design, i.e., 7.6 and 16.8 K$/m for C and D designs respectively. This yields the cost of the arcs of approximately one billion dollars. The cost model used in our study is for the aperture optimization algorithm. Additional costs are included in the Cost Comparisons Report.[7]

(c) It is necessary to mention that Eq.(23) is not the final design parameters. The optimization model is only used in an attempt to make fair coil aperture comparisons among the various magnet types. Several factors may affect the exact values of these choices. For example, if a more effective sorting scheme is found, the results will change. If the magnet errors, especially b_2 and a_2, are different from those given in Table 2, the result will also change. In case the errors are double those of Table 2, the optimum will be

$$d_c = 5.2\text{ cm},\quad L = 140\text{ m}\quad \text{for design C} \tag{24}$$

$$d_c = 5.2\text{ cm},\quad L = 90\text{ m}\quad \text{for design D.}$$

In case the errors are half those of Table 2, the optimum is around

$$d_c = 3.2\text{ cm},\quad L = 170\text{ m}\quad \text{for design C} \tag{25}$$

$$d_c = 3.0\text{ cm},\quad L = 105\text{ m}\quad \text{for design D.}$$

(d) As discussed in Chapter VI, instabilities are not yet a limiting factor if $d_c = 4$ cm. If field errors are improved or the cost model changes so that the optimum inner coil diameter is reduced, attention must be given again to the collective effects.

(e) Five different and essentially independent programs having different emphases have been used to give the predicted apertures. In regions of overlap they are in essential agreement at the ±20% level.

(f) For the nominal ranges of parameters which have been studied, the dominant aperture limitation is due to non-linear magnet errors and not chromaticity correction sextupoles.

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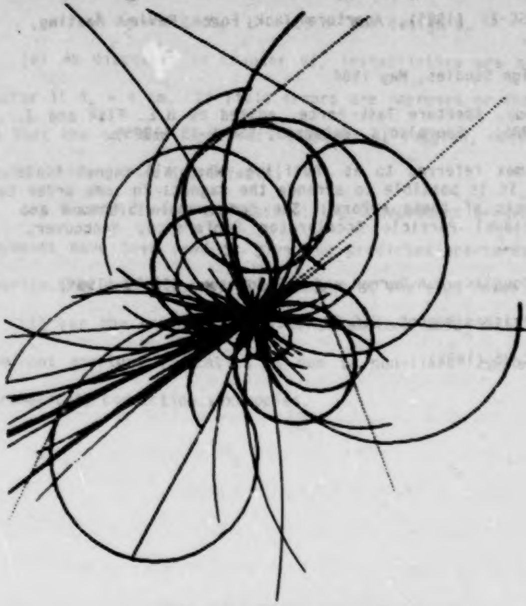
APPENDIX 8

SSC-SR-1012

The Superconducting Super Collider



Cost Comparisons
for
SSC Magnet Dependent Systems

August 15, 1985

SSC Magnet Dependent Systems
Cost Comparison Report

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I. INTRODUCTION

A. Objective

An SSC Cost Estimating Task Force was appointed by the SSC Director in May, 1985. The charge to the task force was to perform a detailed review of costs for all superconducting magnet design styles that are under consideration for the SSC. Cost information on five magnet styles was reviewed in detail by the task force members. The basic cost information was developed by participating laboratories and by industry. Details of the procedure and analysis are presented in Chapter III.

The purpose of this report is to provide a comparison of all SSC construction project cost information that is dependent on the various magnet styles. It is emphasized that the costs displayed in the tables of this report are not the total costs for an SSC construction project. Only those systems for which costs vary with magnet style are included. In Appendix E, current results are compared with the relevant parts of the 1984 SSC Reference Designs Study (RDS) cost estimate.

Following the method used in the RDS, the costs that are developed here are non-site specific. The labor rates utilized are based on a national average for the various labor categories. The Conventional Systems costs for underground structures are derived from an extension of the "median-site" model as described in the RDS.

The results of the 1984 RDS indicate that the superconducting magnet system of the SSC collider ring is a dominant part of the projected technical systems construction costs. This system is also a vital element influencing the size (and hence total project costs) and operating costs for an accelerator project in the SSC energy region. It is therefore important to understand the cost and operational implications of each of the candidate superconducting magnet systems.

There have been numerous developments in the magnet R&D program over the past year. The conceptual designs for the magnet styles of the RDS have been greatly improved and two additional design styles are under consideration. A number of magnet models have been fabricated and tested for these designs. In addition there have been impressive improvements in the development of superconducting cable. The costs of the various magnet styles have been evaluated in light of the improved designs and associated R&D programs.

B. Background

In the 1984 RDS, a detailed Work Breakdown Structure (WBS) was established for the complete SSC project (see Table II-1). The WBS was developed in consultation with HEP construction project managers and experienced accelerator designers. The cost of each WBS element was determined from known or estimated materials and labor costs. Total Project Costs were estimated for three different magnet styles which, for reference, we shall label A(84), B(84), and C(84).

The general philosophy of the RDS approach was to include all construction costs incurred after project approval to bring a 20-TeV colliding beam proton accelerator to a state of operational readiness and to create a laboratory environment suitable for conducting high-energy experiments at the facility. To accomplish this goal and to insure completeness and uniform procedures in cost estimating, a set of guidelines and assumptions were established. These are listed in Table 1-1.

Table I-1
RDS Cost Estimating Guidelines and Assumptions

1. All primary technical components are developed to a state of engineering design readiness.

2. A significant number of main ring production prototype magnets have been produced and tested successfully.

3. The facility is constructed at a median* site within the U.S.

4. Materials costs and labor rates are based on a national average.

5. Past escalation rates, as required for estimating, are determined from DOE records (DOE-HEP-81402).

6. The SSC laboratory administration will manage the construction contracts.

7. Conventional construction contracts will be subcontracted by AE/CM firms.

8. Engineering Design and Inspections (EDI) for technical components will be performed by the laboratory staff.

9. Final assembly and testing of major technical components and systems will be done at the SSC site.

10. The responsibility for risk and quality assurance of major components and systems will be borne by the SSC.

11. The construction period is six years.

---

*See 1984 SSC Reference Design Study Report, page 53.

In addition to the above guidelines, the RDS established that the following items were excluded from the SSC Project Cost Estimate:

- R&D on accelerator systems and components.
- Costs incurred prior to project approval to ensure an orderly and efficient start.
- Site acquisition costs.
- Pre-operation Costs
- Power distribution beyond the site boundary.
- Physics research equipment (e.g. detectors and associated computers).

C. Progress Since the RDS

In this section we list a number of items which represent changes in technical parameters and associated costs from that determined in the RDS.

1. Superconductor Development. At the time of the RDS, superconducting cable of approximately 1900 A/mm^2 was available, and it was assumed that the development program could achieve approximately 2400 A/mm^2 at the time of construction. The developments have occurred much faster than anticipated. As cable up to 2500 A/mm^2 is presently produced and samples to 3000 A/mm^2 have been achieved, 2750 A/mm^2 is now assumed to be available at the time of construction.

2. Design Changes in Previous Magnets. Magnet styles A(84), B(84), and C(84) have evolved over the past year, and the improved designs are labeled A, B, and C in this report. In brief, a collared coil system and an intermediate heat shield have been incorporated into Design A. Design B has an improved cryostat design and magnet support system. Design C has a significant change in magnet length, additional trim coils have been added, and fabrication techniques have been developed further.

3. New Design Styles. Magnet Designs D and C* have been added for consideration. Basically Style D is a "1-in-1" version of Design A, i.e. magnetically and cryogenically decoupled. The latest improvements in

cryostat design have also been incorporated. C* is a "1-in-1" version of Style C which is cryogenically decoupled.

4. Peak Operating Fields. Practical peak operating fields have been evaluated in view of the design changes and the improvements in superconductor. These are as follows for the current designs:

Style	Field (T)
A	6.4
B	5.75
D	6.4
C	3.0
C*	3.0

Prior to this determination, slightly different peak fields were considered for design styles A, B, and D. These are given in the parameter comparison (Section II-C) and carried in the estimating process through Section III-A. In Section III-A-4, an adjustment is made to normalize the cost factors to the currently projected peak operating fields as listed above.

5. Model Tests. All of the magnet designs reflect a high degree of confidence that peak fields and overall field quality can be achieved as a result of actual models tests over the past year.

Five one-meter models have been fabricated and tested at LBL to verify design features of the Design A and D collared coil systems. Four 4.5 m magnets (3 cm bore) of the Design A style were fabricated and tested at BNL. In addition, two 4.5 m models (4.0 cm bore) have been successfully tested at BNL for the D design. At FNAL a number of one-meter models have been fabricated to explore the effects of construction details such as the Cu/SC ratio, helium ventilation, collar stiffness, etc. Also, a 12 m cryostat model was successfully tested to verify the achievement of the projected heak leaks. The TAC program has produced four one-meter models (two "1-in-1" and two "2-in-1") of Design C which have been tested as well as a seven-meter model. A 28-meter unit is currently being assembled by industry from components and subassemblies furnished by TAC.

6. Magnet System Apertures. An SSC aperture task force was created to determine the required aperture for each magnet style. The results are incorporated in Section III A-4 with appropriate cost adjustments.

7. Conventional Facilities. The tunnel unit cost data, as determined in the RDS, have been supplemented by additional information from the current A/E consortium (Raymond Kaiser - Tudor - Keller Gannon & Knight). In particular, case histories of the final costs of 84 tunnels tabulated by the U.S. National Committee on Tunneling Technology serve to confirm the currently projected unit costs.

8. Other Technical Systems. In the RDS the major cost difference for the magnet styles considered was estimated to be in the category of cryogenic systems. With current designs the variation in the costs of cryogenic systems has narrowed. The costs for other systems have been estimated and are presented in Section III-B.

9. Contingency Factors. The contingency analysis of the RDS has been extended in light of the current data. In particular, a more detailed analysis has been used for magnet systems in view of the additional information from the magnet development program noted above.

D. The Current Cost Estimating Model.

The methods used in this report follow closely that of the RDS. The same WBS structure is utilized and the same guideline assumptions apply as listed in Section B above. The current costs reflect the impact of the R&D program of the past year, resulting design improvements, and other factors as summarized in the previous section. The basic information, procedures, and methods of this report are described in Chapter II.

The magnet style costs, as described in Section III-A, were developed from basic cost data provided by the laboratories and, for some magnet styles, by two industrial firms. The basic data was reviewed by the Cost Estimating Task Force (CETF) and its consultants to arrive at a CDG estimate. The CDG estimate reflected corrections and/or additions to the basic cost information to insure an appropriate normalization to the same design goals and cost estimating guidelines.

Finally, in Section III A-4, the CDG estimates are adjusted to the currently prescribed apertures and fields. In order to facilitate comparisons with previous data, the current costs are converted to FY84 dollars.

The costs for other Technical Systems are estimated for each magnet design style in Section III-B. Such systems include cryogenics, vacuum, power supplies, rf, instrumentation, controls, and safety. Costs for these items are evaluated from the basic information developed in the RDS.

Conventional Systems costs are updated in Section III-C to adjust to the conditions required by the current designs. The largest cost item is the collider tunnel for which the circumference (and cost) is scaled to reflect the current design and prescribed peak operating field of each magnet style. Other factors such as roads, tunnel access, and utilities are also evaluated.

In Section III-D and III-E, the EDI and contingency for the elements of this cost estimate are determined. The resulting total costs of the magnet dependent systems for each of the given magnet styles are summarized in Chapter IV.

II. ESTIMATING METHOD AND PROCEDURE

The following sections in Chapter II are brief summary descriptions of the information and materials used in developing, assembling, and analyzing the magnet dependent system cost estimates. The estimating models and background information is described in Section II-A and B; a brief parameter comparison is tabulated in Section II-C. The five magnet designs described as types A, B, C, C*, and D are grouped for convenience into major categories of "Cosine Theta Magnet Styles" and "Superferric Magnet Styles." Within each of these major categories the 2-in-1 designs and 1-in-1 designs are described. The following nomenclature is used:

Cosine Theta Styles:	2-in-1	Design A
	1-in-1	Designs B and D
Superferric Styles:	2-in-1	Design C
	1-in-1	Design C*

A. Estimating Formats

The material is arranged to display all of the appropriate SSC cost elements that are dependent on a particular magnet style. An attempt has been made to estimate explicitly the elements that are "uniquely" required to incorporate each magnet style in the SSC Total Facility. All cost elements have been defined in terms of a WBS element or task. The same seven major WBS categories used for the SSC Cost Estimate in the RDS are considered. This structure is shown in Table II.I for the detail elements as defined to the third WBS level. For this magnet-dependent systems cost comparison report it is assumed that cost factors are affected only in the Collider Facilities, Systems Engineering, and Contingency categories (1.4, 1.6, and 1.7). These WBS categories are expanded to lower levels in Table II.2.

To clarify the cost estimate comparisons, all cost elements presented in this report adhere to this WBS structure. The detailed "bottoms up" cost estimates that were done for each of the magnet styles were based on a "Level 9" WBS table that described the magnet Collider Accelerator System magnets in great detail. These magnet elements fit into the above structure within category 1.4.2.1 (Collider Accelerator Systems - Magnets) in Table II.1.

Table II.1
Work Breakdown Structure for SSC

1. SSC Laboratory
    - 1.1 Project Management and Administration
        - 1.1.1 Construction Project Management
        - 1.1.2 Laboratory Support Services
    - 1.2 Central Laboratory Facilities
        - 1.2.1 Conventional Construction
        - 1.2.2 Equipment
    - 1.3 Injector Facilities
        - 1.3.1 Conventional Construction
        - 1.3.2 Injector Systems
    - 1.4 Collider Facilities
        - 1.4.1 Conventional Construction
        - 1.4.2 Collider Accelerator Systems
    - 1.5 Experimental Facilities
    - 1.6 Systems Engineering and Design
        - 1.6.1 AE/CM Services
        - 1.6.2 Engineering, Design, & Inspection
    - 1.7 Contingency
        - 1.7.1 Conventional Construction
        - 1.7.2 Technical Components

Table II-2
Magnet Dependent Systems Work Breakdown Structure for SSC

- 1.4 Collider Facilities
  - 1.4.1 Conventional Construction
    - 1.4.1.1 Land Improvements
    - 1.4.1.2 Tunnel Enclosure
      - 1.4.1.2.1 Tunnel Type I
      - 1.4.1.2.2 Tunnel Type II
      - 1.4.1.2.3 Tunnel Type III
      - 1.4.1.2.4 Tunnel Other Common Elements
    - 1.4.1.3 Cryogenic Facilities
    - 1.4.1.4 Support Buildings
    - 1.4.1.5 Utility Distribution Systems
    - 1.4.1.6 Special Access Shafts
  - 1.4.2 Collider Ring Systems
    - 1.4.2.1 Magnet Systems
      - 1.4.2.1.1 Tooling
      - 1.4.2.1.2 Dipole Magnets
      - 1.4.2.1.3 Quadrupole Magnets
      - 1.4.2.1.4 Special Devices/Spool Pieces
      - 1.4.2.1.5 Special Magnets/Insertions
      - 1.4.2.1.6 Installation and Survey
    - 1.4.2.2 Cryogenic Systems
    - 1.4.2.3 Vacuum Systems
    - 1.4.2.4 Main Power Supplies
    - 1.4.2.5 Correction Element Power Supplies
    - 1.4.2.6 RF System
    - 1.4.2.7 Injection System
    - 1.4.2.8 Abort System
    - 1.4.2.9 Beam Instrumentation
    - 1.4.2.10 Controls
    - 1.4.2.11 Personnel Protection/Safety

1.6 Systems Engineering and Design
    1.6.1 Conventional Systems
    1.6.2 Collider Facilities
        1.6.2.1 Magnet Systems
        1.6.2.2 Other Technical Systems

1.7 Contingency
    1.7.1 Conventional Systems
    1.7.2 Collider Facilities
        1.7.2.1 Magnet Systems
        1.7.2.1 Other Technical Systems

The detailed costs for the magnet-dependent conventional facilities (e.g., tunnel, cryogenic facilities, etc.) comparisons also follow the WBS format and are described according to an expansion of the 1.4.1 (Collider Facilities - Conventional Construction) section shown in Table II-2. The appropriate AE/CM and Contingency estimates are also described for the Conventional Systems within sections 1.6 and 1.7 accordingly.

All magnet costs that are presented in Section III-A were developed for this study in FY1985 dollars and reflect the nominal apertures, field levels, and lengths as described in the text. For the final machine specific cost comparisons required, certain CDG adjustments to the initially developed magnet costs are made to convert to Reference Designs Report "Cost Comparison Units" (essentially FY84 dollars for simplified RDS comparisons) as well as to address several physical adjustment factors, such as field level, aperture scaling variations, etc. The "Other Technical Components" described in Section III-B are estimated in FY84 dollars for the specific magnet styles, and the Conventional Construction (Section III-C) estimates are normalized to first quarter 1984 costs.

B. Basis for the Estimates

1. Technical Systems

The technical component cost estimates for the various magnet styles were developed in the following manner. The SSC Central Design Group provided a set of "cost estimating guidelines", estimating data sheets, and a detailed WBS to each participating group. All costs for the technical components were separated into "materials" (including not only the price of raw materials but also the complete purchase cost for all "vendor supplied components" for finished machined, fabricated, or purchased units) and "labor" (which included machining and/or fabrication if appropriate, and all assembly, test, inspection, and installation labor). Considerable attention was given to ensure that each group was using the same criteria for costing; standard craft code designators were specified for describing the type of labor required, and standard labor rates were developed to represent an "average" labor market. Labor rates were normalized to a national average to minimize any geographical dependence of the estimate.

The various magnet system detailed costs were estimated both by participating magnet development groups and by industrial manufacturing firms; they were assembled, reviewed, and analyzed by the Central Design Group Cost Estimating Task Force for uniformity, consistency, and completeness. All of the estimates are presented as they were received; the CDG estimates represent the best Task Force projections after a thorough review and analysis.

The basis for the estimate follows the assumptions listed in Table I-1. All primary technical components are assumed to be in an advanced state of development at the start of the construction phase. In particular, the dipole magnet design is presumed to have been fully developed and a significant number of production prototype magnets have been produced and thoroughly tested.

For the technical components, we assume that overall contract management and all administrative functions would be carried out by the SSC laboratory. The technical engineering, design, and inspection (EDI) would be carried out predominantly by laboratory staff. Also it is assumed for this cost comparison model that the major final assembly and testing of the technical components and systems would be carried out at or near the site and that the primary technical risk and quality assurance responsibility will be borne by the laboratory. For the magnet production schedule, a period of five years has been assumed for magnet fabrication (of any style).

The magnet styles being considered and the lead groups responsible for initially developing and providing the primary cost detail materials are indicated below:

Cosine Theta Style Magnets:
Magnet Style A - Tooling and Dipole Magnets, BNL
Magnet Style B - Tooling and Dipole Magnets, FNAL
Magnet Style D - Tooling and Dipole Magnets, BNL & FNAL, GD*, W**
(* General Dynamics, ** Westinghouse)
Superferric Style Magnets:
Magnet Style C - Tooling and Dipole Magnets, TAC, GD, W
Magnet Style C*- Tooling and Dipole Magnets, TAC
Cryogenics A, D - BNL
Cryogenics B - FNAL
Cryogenics C - TAC, CCI (Cryogenic Consultants Inc.)
Conventional Facilities - PB*, RTK**, CDG
(*Parsons Brinckerhoff, ** Raymond Kaiser, Tudor,
Keller & Gannon-Knight)

Note that two industrial firms, General Dynamics and Westinghouse, both provided independent manufacturing plans and cost estimates for tooling and dipole magnets for the two particular styles C and D. For the magnet manufacturing tasks, these studies followed the same outline format, utilized the same WBS elements, and cast their estimates in the same style as the laboratory estimates. The specific "material dollars" and "direct labor hours" were explicitly described. This allows a direct comparison of each of the magnet assembly elements made by each of the estimators. In the industrial estimates, the various methods of addressing certain overall project managing and contracting forms (that each specific industry uses to develop their specific "bottom line" cost elements) are treated as "contract factors" (e.g., purchasing expenses, QA, documentation and reporting, fee or profit, "cost of money" allowances, etc.). These elements from the industrial estimates don't align directly with the SSC WBS factors and cost model that includes Project Management, EDI (Engineering, Design, and Inspection), Contingency, etc.

General Dynamics extends their "material" and "factory labor hours" estimate to provide a model corresponding to a single industrial subcontract (e.g., with GD Convair Division in San Diego) under which they would manufacture all the tooling and dipole magnets required. They would assume certain project risk by contracting for more project responsibility by providing all necessary project management, QA, purchasing, material handling, testing, etc. This, of course, is not the model that we follow here for the cost comparison study. However, for such a manufacturing model we present a correlation (as shown in the detail analysis sections below and in the Appendix) between the laboratory, industry, and CDG estimates that allow direct comparisons of the "bottom line" costs as well as just the magnet fabrication cost.

The original model that was assumed for the Reference Designs Study remains a common basis for this comparison analysis. Although the costs of the various magnet dependent systems were developed and presented by the technical teams from the participating laboratories and industry; all data have been reviewed and analyzed by the CDG task force before a CDG assessment estimate was made. The overall responsibility for the SSC cost estimates presented in this report rests with the SSC Central Design Group.

2. Conventional Systems

In the RDS, the SSC collider ring, which determines the size of the required site, had a circumference of 56 to 100 miles depending upon the magnetic field used. The collider ring components are confined to an underground tunnel and to the surface buildings placed near the tunnel.

Buildings next to (or straddling) the tunnel roughly every 5-8 miles contain power supplies, helium refrigeration systems, and points of access to the tunnel. At six locations around the ring, other buildings intersect the tunnel and house the facilities for experiments in the interaction regions where the two circulating beams collide. The Injector and Central Laboratory were located in a campus-like configuration adjacent to the position of the collider.

The conventional system designs for the RDS were developed by an architectural/engineering firm, Parsons Brinckerhoff (PB). At a preconceptual level they prepared a technical design such that it was possible to generate a cost estimate. Following guidance from the technical groups, the PB engineers produced fifty drawings, numerous tables, outline schedules, and several reports covering the following topics:

WBS	1.2.1	Central Laboratory Facilities
	1.3.1	Injector Facilities
	1.4.1	Collider Facilities
	1.5.1	Experimental Facilities
	1.6.1	Estimates for AE/CM Services
	1.7.1	Contingency Estimate

The objective of the current effort, as in the RDS, is to provide a cost estimate that is appropriate prior to the selection of a specific SSC site. In this regard national data bases were used for labor costs, materials, average tunnel costs, etc. Local geotechnical condition appropriate to specific sites represent variances about these average numbers. As noted in the previous section, the Collider Facilities are affected by the magnet style together with the estimated AE/CM Services and Contingency. The ring circumference in the current estimates is appropriately updated to reflect the projected peak operating fields of the present designs.

C. Magnet Parameter Comparison

The five basic dipole magnet styles are described briefly below. A parameter summary comparison table is shown in Table II-3.

COSINE THETA STYLES:

Type A is a High Field (6T) superconducting magnet utilizing a two layer collared cosine-theta coil (stainless-steel collars), cold iron for the flux return, and arranged with two bores in one single yoke (e.g. 2-in-1) all contained in a single cryostat. The coil i.d. is 4 cm and the bore tube i.d. is 3.28 cm The magnet has an effective magnetic length of 16.6 m and an overall length of 17.6 m. For a 20-TeV SSC, 4200 such magnets would be required if the central field is 6T. The Type A design has been developed by LBL and BNL.

Type B is a high field (5.5T) magnet utilizing a two-layer collared cosine-theta coil (with aluminum collars) and no "cold iron." The outer vacuum vessel is a "warm iron" shell that provides magnetic shielding; the magnets

TABLE II - 3

MAGNET STYLE PHYSICAL PARAMETERS

(Nominal Design Values, Not reflecting CDG cost scaling adjustments for Field, aperture, length, etc.)

	COSINE THETA STYLES			SUPERFERRIC STYLES	
	A	B	D	C	C*
CENTRAL FIELD, T	6.0	5.5	6.0	3.0	3.0
MAGNETIC LENGTH, M	16.6	11.25	16.6	35.0	35.0
2-IN-1 OR 1-IN-1	2-IN-1	1-IN-1	1-IN-1	2-IN-1	1-IN-1
NO. REQD FOR SSC	4200	13392	8400	4000	8000
BORE ID, CM	3.28		3.28	2.5 X 3.2	2.5 X 3.2
BORE TUBE MATERIAL	NITRONIC 40	ALUMINUM	NITRONIC 40	STAINLESS	STAINLESS
COIL ID, CM	4.0	5.2	4.0	width: 4.5	width: 4.5
NO. COIL TURNS; INNER, OUTEP	2X(32, 40)	48, 37	32, 40	2X(2(trim), 4, 4)	2(trim), 4, 4
CONDUCTOR LENGTH/MAGNET, ft	2X(3664, 4648)	3670, 2830	3664, 4648	2X(472(trim), 1890)	472(trim), 1890
COIL COLLARS, MAT'L	NITRONIC 40	ALUMINUM	NITRONIC-40	NA	NA
NO. COLLARS/MAGNET, STAMPINGS	2X20300		20300	NA	NA
NO. YOKE LAMINATIONS, PIECES	2x21150	NA	21150	3X22920	2X22920
LAMINATION THICKNESS, IN.	.060	NA	.060	.060	.060
LAMINATION CROSS SECTION, IN.	14.0 DIA	NA	10.5 DIA	5.5X9.27 EQUIV	5.5X4.45 EQUIV
WT. LAMINATION MAT'L REQD/MAGNET, LBS.	39400	NA	22900	24900	12600
CRYOSTAT/VACUUM VESSEL OD, IN.	27.5	26.0	24.0	16.75	12.5
VACUUM VESSEL MATERIAL	STEEL	STEEL	STEEL	ALUMINUM	ALUMINUM
HEAT SHIELDS AT TEMPERTURES, K.	20, 80	10, 80	20, 80	10, 80	10, 80
NUMBER LAYERS MULTI-LAYER INSULATION	40	40	40	65	65
INTERNAL COLD MASS SUPPORTS, NUMBER	5	5	5	5	5
SUPPORT POST TYPE,	PEDESTAL	PEDESTAL	PEDESTAL	PEDESTAL	PEDESTAL

are all single bores (1-in-1). The coil i.d. is 5 cm; the overall length is 12 m (magnetic length 11.25 m), and approximately 13400 such magnets are required for 5.5T operation. Style B was developed by FNAL.

Type D represents a magnetically and cryogenically decoupled version of style A. Magnetic parameters are similar. Approximately 8400 units at 6T central field operation are required for the SSC. Style D is being developed by a collaboration of BNL, FNAL, and LBL.

SUPERFERRIC STYLES:

Type C is a low field (3T) superferric magnet developed by TAC. This magnet has cold iron, and is arranged for 2-in-1 magnetically decoupled units to be mounted vertically in a single cryostat. The iron gap is 2.5 cm high and 3.2 cm wide for the useful aperture. Each bore of the magnet has three separately energized coils that are adjusted to tune out unwanted multipoles, and each coil set must follow a prescribed ramping program sequence. These magnets are fabricated in 35 m elements, three each of which are preassembled or joined together at the laboratory site to form 105 m long dipole units. A total of 1333 of these long units (or 4000 of the fabricated 35 m units) are required for the SSC.

Type C* is the same style as C with the same magnetic geometry and parameters, but utilizes two independent 1-in-1 magnets contained in separate cryostats. Hence for C*, 2666 each of the long units (or 8000 fabricated 35 m units) would be required for the SSC. Style C* is also being developed by TAC.

III. COST ESTIMATES AND ANALYSIS

This chapter presents the detail cost estimate materials for comparison and discussion. Section III-A contains costs for all of the five magnet system styles; Section III-B contains the "Other Technical Components" costs, and III-C discusses the Conventional Facilities Costs. Sections III-D and III-E contain the CDG analysis for EDI and Contingency.

A. Magnet Systems

1. Summary and Overall Magnet Comparisons

The cost summary material is arranged to display the cost estimate totals for all of the magnet systems in this section (Section 1), and to provide detail comparisons and analysis for the cosine theta and superferric magnet styles in the next two sections (Section 2 and Section 3) respectively. The CDG adjustments to the costs are discussed in Section 4. The construction model assumed for the magnet fabrication has been discussed in the "basis for the estimate" in Section II-A.

The collider ring magnet system as defined by the total WBS 1.4.1 category comprises not only the ring dipole magnet elements, but also the corresponding quadrupole magnets, spool piece elements, "special" insertion region magnets, and the final installation and ring survey. During the RDS, all of these various components were defined and costed explicitly as described in Appendix C of the RDS Report. For this cost comparison study, certain of these magnet-dependent specific systems were re-examined and costed in detail (e.g., styles D and C quadrupoles and spools, installation), and certain systems received only a rather brief re-examination (e.g., style A and B quads, spools, etc.). Additional new elements for style C* have not been considered or designed in any detail; cost values for C* estimates are developed largely by extension from style C. In areas where "new data" are not developed explicitly for this cost comparison report, the earlier RDS data are used. Where these data are used, they were carefully updated to current fiscal year conditions (escalated), and scaled for quantity, aperture conformance, etc.

Also, in order to represent the total magnet system costs, it is necessary to consider appropriate portions of the Engineering, Design, and Inspection and Contingency costs. A discussion of the "EDI" factors and the Contingency to be applied to the estimates is included in Section III-D and III-E.

With these comments in mind, the summary data presented in Table III-1 may be studied. These costs are the CDG "adjusted" values that were developed in Section III-A-4, and represent figures for the total magnet system for each magnet style after adjustments for field level, aperture, and FY1984 costs are made. A comparison and discussion of the cost data for the magnet systems follow in the next sections. The dipole magnet cost data are fully developed and compared in detail. (Additional cost comparison discussion appear in the Appendix.) The other special magnet elements and other related systems are discussed, but the material is generally at a more summary level.

TABLE III - 1
MAGNET SYSTEM COST COMPARISON SUMMARY
ADJUSTED MAGNET SYSTEM COSTS
FY1984 K$

(WBS) 1.4.2.1. STYLE:	A	B	D	C	C*
1 TOOLING	41,497	23,738	41,497	21,810	21,810
2 DIPOLE MAGNETS	573,837	642,937	646,421	278,358	384,744
3 QUADRUPOLE MAGNETS	38,341	54,346	42,397	19,048	24,762
4 SPEC. DEVICES/SPOOLS	37,543	75,818	67,874	84,667	110,067
5 SPEC. MAGNETS/INSERTIONS	14,286	14,286	14,286	14,286	14,286
6 INSTALLATION & SURVEY	26,750	58,765	40,833	23,306	34,286
TOTAL ADJUSTED MAG SYS	732,254	869,890	853,309	441,473	589,953

2. Cosine Theta Magnet Styles: A, B, and D

a. Dipoles. All costs presented in this section (and section 3 for superferric styles) represent the "unadjusted" parameter costs. Some of the statements and descriptions below as they pertain in general to the WBS element descriptions and to the evaluation and analysis of the industrial participant cost estimates will also apply generally to the superferric styles as well. The material that is presented as the CDG estimate is based on a careful review and analysis of the cost estimate details that were developed by the laboratory and industrial participants. The first part of Table III-2 (dipole unit costs) shows the CDG compilation of the WBS "level 7" summary of detail elements for the three cosine theta dipole magnets. In general the cost estimates were developed by the participants at WBS "level 9" detail, and then summed to various higher levels for comparisons.

Each of the cost tables will show four columns as indicated for a) Material Dollars, b) Labor Hours, c) Labor Dollars, and d) Total Dollars. The subtotal represents a "per magnet" cost according to the manufacturing production model, and the labor rate ($/hr) conversion as developed by the CDG and supplied to all the cost estimating participants for common use.

The lower portion of Table III-2 shows the total costs estimated for all of the dipole magnets. The tooling cost corresponds to the manufacturing cost to replicate the rate-tooling necessary to meet the magnet production schedule, and the total dipole cost is simply the product of the number of magnets times the "per magnet" price.

A brief definition of the WBS "level 7" elements will aid in the comparisons. In general there is a direct "row by row" correspondence for all of the magnet styles, but in some cases the absolute boundary or interface between certain tasks or materials becomes "fuzzy" and certain items may be interpreted and collected by various estimators under different low level categories. This is not a problem for the major and well-defined systems that are clearly common to all systems (e.g., bore tube, coils, coil collaring, yoke and components, and the "cold mass" helium containment vessel.) However, due to the differences in the specific designs, certain of the cryostat elements were not as "common" and some decision had to be made in terms of which WBS category was most appropriate for cost groupings. For example, the WBS listing has separate "level 7 collections" for upper, lower, and ends of the vacuum vessel. This was appropriate for the Designs A and D where the vacuum vessel was

TABLE III-2
COSINE THETA STYLE DIPOLE MAGNET COMPARISONS

COSINE THETA STYLE MAGNET COMPARISONS
UNIT COSTS PER DIPOLE MAGNET

(WBS)	ITEM:	COS THETA STYLE A CENTRAL DESIGN GROUP ESTIMATE				COS THETA STYLE B CENTRAL DESIGN GROUP ESTIMATE				COS THETA STYLE D CENTRAL DESIGN GROUP ESTIMATE			
		MATL $	LBR HRS	LABOR $	TOTAL $	MATL $	LBR HRS	LABOR $	TOTAL $	MATL $	LBR HRS	LABOR $	LABOR $
C	MAGNETS - DIRECT MATLS AND LABOR, (FACTORY)												
14212. 1.1	COLD BORE TUBE	5273.0	68.5	1575.5	6848.5	410.0	30.0	690.0	1100.0	2536.0	34.3	788.9	3424.9
1.2	COILS	65750.0	292.9	6736.7	72486.7	23480.0	120.0	2760.0	26240.0	32875.0	146.5	3369.5	36244.5
1.3	COIL COLLARING	12202.8	69.6	1600.8	13803.6	3941.0	30.0	690.0	4631.0	6141.0	34.8	800.4	6941.4
2.1	YOKE AND COMPONENTS	15870.0	43.6	1002.8	16872.8	0.0	0.0	0.0	0.0	9341.0	38.7	890.1	10231.1
2.2	HELIUM CONTAINMENT VESSEL	5444.6	16.6	381.8	5826.4	2186.0	44.0	1012.0	3198.0	3196.0	14.4	331.2	3527.2
3.1	COLD MASS SUBASSEMBLY PREP	832.2	15.3	351.9	1184.1	7534.0	0.0	0.0	7534.0	803.0	15.0	345.0	1148.0
3.2	20K HEAT SHIELD	912.9	18.9	434.7	1347.6	2342.0	0.0	0.0	2342.0	913.0	18.9	434.7	1347.7
3.3	80K HEAT SHIELD	2558.4	18.7	430.1	2988.5	1064.2	42.8	984.4	2048.7	2173.0	18.7	430.1	2603.1
3.4	UPPER VACUUM VESSEL	3562.8	14.5	333.5	3896.3	0.0	31.4	722.2	722.2	2883.0	14.5	333.5	3216.5
3.5	LOWER VACUUM VESSEL	1744.6	19.6	450.8	2195.4	0.0	0.0	0.0	0.0	1471.0	18.6	460.0	1931.0
3.6	VESSEL ENDS	475.5	13.0	299.0	774.5		61.2	1407.6	1407.6	415.0	13.0	299.0	714.0
4.1	INTERNAL BUS WORK	3553.7	103.0	2369.0	5922.7	560.0	5.0	115.0	675.0	1776.9	51.5	1184.5	2961.4
5.1	INTERCONNECTION REGION PARTS	5000.0	22.0	506.0	5506.0	2700.0	20.0	460.0	3160.0	3600.0	22.0	506.0	4106.0
5.2	SHIPPING/STORAGE/HANDLING	30.0			30.0	30.0			30.0	30.0			30.0
6.1	TESTING		8.0	184.0	184.0		8.0	184.0	184.0		8.0	184.0	184.0
6.2	WARM MAGNETIC MEASUREMENTS		16.0	368.0	368.0		8.0	184.0	184.0		8.0	184.0	184.0
6.3	COLD MAGNETIC MEASUREMENTS	150.0	8.0	184.0	334.0	150.0	4.0	92.0	242.0	150.0	4.0	92.0	242.0
6.4	CRYOGENIC TESTING FACILITY OPERNS.		4.0	92.0	92.0		4.0	92.0	92.0		4.0	92.0	92.0
8.1	DIRECT SHOP SUPPORT				0.0				0.0				0.0
8.2	MISCEL. AND INDIRECT SHOP SUPPORT	200.0	180.0	5760.0	5960.0		100.0	3200.0	3200.0	200.0	110.0	3520.0	3720.0
	MATERIAL FACTORS & ALLOWANCES	4000.0			4000.0	1300.0			1300.0	2000.0			2000.0
	ALLOWANCE FOR REJECTS	2000.0	14.0	322.0	2322.0	675.0	7.0	161.0	836.0	1120.0	10.0	230.0	1350.0
	SUBTOTAL	129640.5	946.2	23382.6	153023.1	46460.2	515.4	12754.2	59214.4	71723.9	585.9	14465.7	86189.6

FOR TOTAL DIPOLE MAGNET PRODUCTION,	STYLE A	STYLE B	STYLE D
NUMBER OF DIPOLE MAGNETS TO BE PRODUCED:	4200.0	13392.0	8400.0
TOOLING REQ'D:	46,477 K$	26,058 K$	46,477 K$
TOTAL COST FOR DIPOLE MAGNETS:	642,697 K$	793,000 K$	723,992 K$
TOTAL DIPOLE MAGNET PRODUCTION:	689,174 K$	819,058 K$	770,469 K$

constructed in this manner, but is not directly appropriate for Design B that has a single vacuum vessel. (Style C and C* have "upper" and "lower" components, but no separate "ends".) The shields, cryogenic tubing, and superinsulation also were occasionally collected together by the estimators for convenience. We have made an attempt to separate and keep the WBS levels as common and as well defined as possible; however, the direct comparison between each of the magnets at each "row" level should not be considered exact in each case, and occasionally it is necessary and more proper to compare groups of rows. For example, usually the entire cryostat system can accurately be compared for all magnets, but the individual supports, alignment, and various assembly tasks might not be as easily compared.

The entry for "Interconnection Region Parts" collects the costs of the materials (and any preparation labor) for connecting the dipole magnets in the ring. These are the dipole interconnections only and are not to be confused with the "Special Devices/Spools" that are associated with groups of dipoles (e.g., at each half cell) and are discussed separately. The labor of assembling/installing the interconnection region is covered with the installation costs.

The WBS category entry for a "shipping/storage/handling" allowance provides nominal material and labor for preparing the elements for movement, transport, or storage.

The categories for "Testing", "Warm and Cold Measurements", and "Cryogenic Testing Facility Support" cover the technician and factory/shop personnel required to perform the inspection and testing of the final magnet assembly. Typically this will cover the final electrical, mechanical, vacuum, and cryogenic checks, as well as the magnetic measurement support. The magnet measurement model assumes that every magnet will have complete "warm" measurement tests, and that 10% of the final production magnets will have complete "cold" measurements made. Additional program management and magnet QA, inspection, and test functions are covered in the CDG model as a part of EDI. (In addition to the EDI and the "final magnet assembly" checkout functions above, there is some direct labor called out at the manufacturing and subassembly steps for progress checkout and tests.)

The categories for "Direct" and "Indirect" Shop Support cover the additional personnel in the magnet factory that are not covered in the labor "overhead" burden, and are not costed directly as a task/labor direct operation. Such elements as supervision, materials transport, parts handlers, machine loaders, rigging, and many other "indirect" personnel must be accounted for here. The model used after analysis of the BNL production evaluations and from the TAC projections indicates that approximately 23-25% of the direct labor must be added in this way to cover these necessary functions.

The "Materials Factors and Allowances" are allowances to project material use variances, damaged or unusable materials, excess purchases, etc. We use an allowance of 5% for all of the superconducting materials, (to cover such items as short cable lengths at the ends of reels, damaged and unusable materials, "short-sample" testing materials, etc.) and 1% of all other materials.

The "Reject Allowance" factor uses a production model that assumes 1% of the final magnets are not acceptable and are rejected as unusable, and an additional 1% of all the coils that have been fabricated are unusable. This model assumes that all of the materials and labor are completely lost. In reality, some larger portion of the magnets will undergo some "rework" labor to be saved, and a smaller portion may actually be totally lost. This allowance model is an attempt to project a production capability that must reach this loss level.

b. Total Magnet Systems. The complete magnet system includes the tooling, dipole, quadrupoles, special devices/spool pieces, special magnets for insertions, installation, etc. These elements and their unadjusted costs are shown at the summary level in the table below in FY85 dollars.

In general, all of the "Total Magnet Systems" cost elements for Design A are projections from the new Design D data base. There has been no new direct design effort or separate detailed cost estimate for any of these Design A or B system elements by either the laboratories or industry. All of the A and B estimates were extended and projected by prorating certain major elements of the Design D totals or by extending the RDS work.

Table III-3
Cosine Theta Style Magnet System
(Unadjusted Costs - FY85 K$)

WBS Element	Style A	Style B	Style D
Tooling	46,477	26,058	46,477
Dipole Magnets	642,697	793,000	723,992
Quadrupole Magnets	42,942	67,030	47,485
Special Devices/ Spools	42,084	83,228	76,019
Special Magnets/Insertions	15,000	15,000	15,000
Installation and Survey	29,960	64,508	45,733
TOTAL MAGNET SYSTEMS:	819,124	1,048,824	954,706

For the Design D system, a review of the earlier RDS estimate for the Design A(84) quadrupoles combined with a current estimate for the required length and strength required for Type D resulted in an overall estimate of 28,265$ (each magnet) being arrived at by the CDG study. This was the value used above (for each of the 1680 Design D quads required - 47485K$ total). The quadrupole estimate for styles A and B was updated from the RDS data.

The "Special Device/Spool" category includes not only the correction element windings and spool pieces and half-cell interconnection region hardware, but also an assortment of cryogenic, mechanical, and electrical apparatus. No recent design or cost effort has been included in this study; the RDS data is still the most appropriate basis for projection. We use the same relative scaling factors (0.065 and 0.105 times the dipole cost respectively) for Styles A and B as used in the RDS, and rely on the "B" scaling factor (0.105) to be the most appropriate factor to be assumed for Style D.

The "Special Magnet" category includes the quadrupoles and other apparatus for the insertion regions. These items have not been re-examined, and the CDG estimate simply relies on an average allowance of 15,000K$ to be adequate for all magnet systems. (This is approximately the RDS value adjusted for all systems.)

The "Installation and Survey" cost estimate for Design D was studied separately by the CDG. The results of this study show a cost estimate of 8,976K$ for special installation/survey/checkout tooling and equipment, 9,207K$ for final pre-assembly and test, 4,904K$ for overall installation, and 22,646K$ for final checkout. The total for all these tasks is 45,733K$. This is the estimate we project for the final magnet systems installation for Style D. Styles A and B receive the same installation costs as used in the RDS.

3. Superferric Magnet Styles; C and C*

a. Dipoles. All costs presented in this section (as in section 2 above for cosine theta styles) represent the "unadjusted" parameter costs. The statements and descriptions presented before for the cosine theta style as they pertain in general to the WBS element descriptions and the evaluation and analysis of the industrial participant cost estimates also apply to the superferric styles as well. The material that is presented as the CDG estimate is based on a careful review and analysis of the cost estimate details that were developed by the laboratory and industrial participants. The upper portion of Table III-4 (dipole unit costs) shows the CDG compilation of the WBS "level 7" summary of detail elements for the two superferric dipole magnets.

The lower portion of Table III-4 shows the total costs estimated for all of the dipole magnets. The tooling cost corresponds to the manufacturing cost to replicate the rate-tooling necessary to meet the magnet production schedule, and the total dipole cost is simply the product of the number of magnets times the "per magnet" price.

b. Total Magnet Systems. The complete magnet system costs (unadjusted) for the tooling, dipoles, quadrupoles, spool pieces, special magnets, installation, etc. are shown at the summary level in Table III-5.

TABLE III-4
SUPERFERRIC STYLE DIPOLE MAGNET COMPARISONS

SUPERFERRIC STYLE MAGNET COMPARISONS
UNIT COSTS PER DIPOLE MAGNET

		ITEM:	SUPERFERRIC STYLE C CENTRAL DESIGN GROUP ESTIMATE				SUPERFERRIC STYLE C* CENTRAL DESIGN GROUP ESTIMATE			
(WBS)			MATL $	LBR HRS	LABOR $	TOTAL $	MATL $	LBR HRS	LABOR $	TOTAL $
C		MAGNETS - DIRECT MATLS AND LABOR, (FACTORY)								
14212.	1.1	COLD BORE TUBE	4735.0	42.1	968.3	5703.3	2367.5	21.0	483.0	2850.5
	1.2	COILS	15935.0	80.2	1843.7	17779.5	7068.0	40.1	922.3	8090.3
	1.3					0.0				0.0
	2.1	YOKE AND COMPONENTS	12453.0	106.9	2458.7	14911.7	7353.0	81.0	1863.0	9216.0
	2.2	HELIUM CONTAINMENT VESSEL	1760.0	33.3	765.9	2525.9	2760.0	30.0	690.0	3450.0
	3.1	COLD MASS SUBASSEMBLY PREP (& CRYOSUP)	2264.6	33.0	759.0	3023.6	1900.2	30.0	690.0	2590.2
	3.2	10K HEAT SHIELD	2457.2	56.0	1288.0	3745.2	2400.0	50.0	1150.0	3550.0
	3.3	60K HEAT SHIELD	3632.4	10.0	230.0	3862.4	3600.0	8.0	184.0	3784.0
	3.4	VACUUM VESSEL	3855.2	61.0	1403.0	5258.2	5345.4	61.0	1403.0	6748.4
	3.5					0.0				0.0
	3.6					0.0				0.0
	4.1	INTERNAL BUS WORK	7380.0	40.0	920.0	8300.0	3690.0	20.0	460.0	4150.0
	5.1	INTERCONNECTION REGION PARTS	200.0			200.0	200.0			200.0
	5.2	SHIPPING/STORAGE/HANDLING	61.2	6.0	138.0	199.2	61.2	6.0	138.0	199.2
	6.1	TESTING		8.0	184.0	184.0		6.0	138.0	138.0
	6.2	WARM MAGNETIC MEASUREMENTS		16.0	368.0	368.0		8.0	184.0	184.0
	6.3	COLD MAGNETIC MEASUREMENTS		8.0	184.0	184.0		4.0	92.0	92.0
	6.4	CRYOGENIC TESTING FACILITY OPERNS.	150.0	8.0	184.0	334.0	150.0	4.0	92.0	242.0
	8.1	DIRECT SHOP SUPPORT				0.0				0.0
	8.2	MISCEL. AND INDIRECT SHOP SUPPORT	200.0	120.0	3840.0	4040.0	100.0	84.0	2688.0	2788.0
		MATERIAL FACTORS & ALLOWANCES	1200.0			1200.0	800.0			800.0
		ALLOWANCE FOR REJECTS	1020.0	10.0	230.0	1250.0	510.0	5.0	115.0	625.0
		SUBTOTAL	57304.4	638.5	15764.6	73069.0	39205.3	450.1	11292.3	50497.6

FOR TOTAL DIPOLE MAGNET PRODUCTION,	STYLE C	STYLE C*
NUMBER OF DIPOLE MAGNETS TO BE PRODUCED:	4000.0	8000.0
TOOLING REQ'D:	22,900 K$	22,900 K$
TOTAL COST FOR DIPOLE MAGNETS:	292,276 K$	403,981 K$
TOTAL DIPOLE MAGNET PRODUCTION:	315,176 K$	426,881 K$

Table III-5
Superferric Style Magnet System
(Unadjusted Costs - FY85 K$)

WBS Element	Style C	Style C*
Tooling	22,900	22,900
Dipole Magnets	292,276	403,981
Quadrupole Magnets	20,000	26,000
Special Devices/ Spools	88,900	115,570
Special Magnets/Insertions	15,000	15,000
Installation and Survey	24,471	36,000
TOTAL MAGNET SYSTEMS:	463,547	619,451

In general, all of the "Other Magnet Systems" cost elements for Design C* are projections from the Design C data base. There has been no new design effort or separate detailed cost assessment for any of the Design C* elements by either the laboratories or industry. All of the C* estimates were extended and projected by prorating certain major elements of the Design C totals or by extrapolation from the RDS work.

For Design C, a review of the earlier RDS estimate for the quadrupoles and a new readjustment/projection scaling for the required length and strength estimates resulted in an overall estimate of 20000K$ being arrived at by the CDG study. This was the value selected above and assumed appropriate for Style C. For Style C* a value of 26000K$ was estimated.

The "Special Device/Spool" category includes not only the correction element windings and spool pieces and half-cell interconnection region hardware, but also an assortment of cryogenic, mechanical, and electrical apparatus. A current design and cost estimate ($56700 each) has been presented by CCI (Cryogenic Consultants, Inc.), and forms the basis for the estimate that is projected by the CDG. In order to add an allowance for the superconducting correction coils for the two bore tubes, and to allow for the complex diode package for the several electrical circuits and the interconnections necessary within the "spool piece," an additional allowance of $10,000 per spool was assumed (the same allowance as was used in the RDS C(84) cost estimate). The overall CDG estimate is for a unit cost of $66,700 each for the 1333 half-cell interconnections, or an overall total of approximately 88,900K$. The interconnection boxes for design C* were taken to cost approximately 30% more, 115,570K$ total, in accordance with the 30% ratio for the overall difference between C and C*.

The "Installation and Survey" cost estimate for Design C was studied separately by the CDG. The results of this study show a cost estimate of 6,056K$ for special installation/survey/checkout tooling and equipment, 9,838K$ for final pre-assembly and test (pre-joining and tests for three each 35 m long dipoles into one 105 m long assembly unit for installation in the tunnel), 2,944K for overall installation, and 5,633K$ for final checkout. The total for all these tasks is 24,471K$. This is the estimate we project for the final magnet systems installation. Design C* is projected at 36,000K$.

4. CDG Adjustments

Section 4 describes the adjustments to be factored into the magnet systems estimates to account for the SSC machine specific parameters to be used in the cost comparison study. The adjustments are made in three steps, and a separate table is shown below after each adjustment has been made. The adjustments are made to reflect peak operating field level, magnet aperture conformance, and FY1984 dollars. Table III-6 repeats the cost estimates for the "unadjusted" magnet system values below (repeated from Sections 2 and 3).

Peak Operating Field. Based upon magnet model results and recently improved superconductor we believe that the operating field level of the cosine theta magnets should be adjusted upward accordingly: 5.75T for Design B; 6.4T for Designs D and A (SSC-N-23). The adjustment for field level results in an effective change in the number of dipole elements since we assume that the total product of field level times the effective bending magnet system length must remain constant. We assume that the individual magnet length remains constant and that therefore the total number of magnets required scales as the ratio of field levels. The tooling for production also scales approximately with the number of elements required, and the number of quadrupoles, spool pieces, and the installation and survey requirements also vary nearly directly with the number of dipole elements. The special magnets are required for the insertion regions and remain constant with main ring dipole field level. The operating field level projected and resulting number of dipole magnets for the various magnet styles is shown in Table III-7.

Table III-6
Magnet System Cost Comparison Summary
Unadjusted Parameters
(FY85 K$)

	A	B	D	C	C*
UNADJUSTED PARAMETER VALUES:					
FIELD LEVEL, T	6.00	5.50	6.00	3.00	3.00
NUMBER OF DIPOLES:	4,200	13,392	8,400	4,000	8,000
APERTURE, (DIA: A,B,D; GAP: C,C*),CM:	4.00	5.00	4.00	2.54	2.54
MAGNET SYSTEMS, WBS 1.4.2					
TOOLING	46,477	26,058	46,477	22,900	22,900
DIPOLE MAGNETS	642,697	793,000	723,992	292,276	403,981
QUADRUPOLE MAGNETS	42,942	67,030	47,495	20,000	26,000
SPEC. DEVICES/SPOOLS	42,048	83,228	76,019	88,900	115,570
SPECIAL MAGNETS/INSERTIONS	15,000	15,000	15,000	15,000	15,000
INSTALLATION & SURVEY	29,960	64,508	45,733	24,471	36,000
TOTAL MAGNET SYSTEMS:	819,124	1,048,824	954,706	463,547	619,451

Table III-7
Magnet System Cost Comparison Summary
Adjusted Field Level
(unadjusted aperture)
(FY85 K$)

	A	B	D	C	C*
ADJUSTED PARAMETER VALUES:					
ADJUSTED FIELD LEVEL, T	6.40	5.75	6.40	3.00	3.00
ADJUSTED NUMBER OF DIPOLES:	3,938	12,810	7,875	4,000	8,000
APERTURE, (DIA: A,B,D; GAP: C,C*),CM:	4.00	5.00	4.00	2.54	2.54
FIELD LEVEL/QUANTITY SCALING FACTOR:	.938	.957	.938	1.000	1.000
(* INDICATES ITEMS ADJUSTED)					
MAGNET SYSTEMS, WBS 1.4.2					
* TOOLING	43,572	24,925	43,572	22.900	22.900
* DIPOLE MAGNETS	602,520	758,522	678,742	292,276	403,981
* QUADRUPOLE MAGNETS	40,258	64,116	44,517	20,000	26,000
* SPEC. DEVICES/SPOOLS	39,420	79,609	71,268	88,900	115,570
SPECIAL MAGNETS/INSERTIONS	15.000	15.000	15.000	15,000	15.000
* INSTALLATION & SURVEY	28,000	61,703	42,875	24,471	36,000
TOTAL MAGNET SYSTEMS:	768,066	1,003,875	895,974	463,547	619,451

Aperture. In order to make the adjustment for required aperture, a study was made to examine the cost effect for a 1.0 cm aperture or gap perturbation for each of the magnet styles (Appendix C). An appropriate scaling factor at each "level 7" cost table entry was applied separately for materials and labor. The resulting total cost was then derived and used to determine normalized overall aperture scaling factors; in this case we project a factor for a 1.0 cm decrease for Style B. The resulting overall aperture scaling factor of 0.890 was developed to scale from a Style B 5.0 cm bore to a 4.0 cm bore.

Table III-8 shows the magnet system costs after the aperture scaling factor has been applied. We assume that the tooling, special devices (cryogenic interconnections and spool pieces), and installation and survey are independent of aperture, and that dipoles and quadrupoles are both scaled directly with the aperture factor.

The resulting apertures used here for the various designs are consistent with those values determined by the Aperture Task Force through a detailed calculation analysis (SSC-SR-1013).

FY 1984 Cost. The final adjustment we make is to convert from current FY1985 to RDS-FY1984 dollars to allow a summation with the other Technical Systems costs and Conventional Systems costs and to permit direct comparisons to be made with the RDS data. We assume an overall escalation/inflation rate of 5% for FY1984; therefore the adjustment is made by dividing all FY85 costs by 1.05 to approximate equivalent FY84 costs. Using this overall factor, then, the final adjusted table for the Magnet System costs is shown in Table III-9.

Table III-8
Magnet System Cost Comparison Summary
Adjusted Field Level
Adjusted Aperture
(FY85 K$)

	A	B	D	C	C*
ADJUSTED PARAMETER VALUES:					
ADJUSTED FIELD LEVEL, T	6.40	5.75	6.40	3.00	3.00
ADJUSTED NUMBER OF DIPOLES:	3,938	12,810	7,875	4,000	8,000
APERTURE, (DIA: A,B,D; GAP: C,C*),CM:	4.00	4.00	4.00	2.54	2.54
FIELD LEVEL/QUANTITY SCALING FACTOR:	.938	.957	.938	1.000	1.000
APERTURE SCALING FACTOR:	1.000	.890	1.000	1.000	1.000
(* INDICATES ITEMS ADJUSTED)					
MAGNET SYSTEMS, WBS 1.4.2					
TOOLING	43,572	24,925	43,572	22,900	22,900
* DIPOLE MAGNETS	602,528	675,084	678,742	292,276	403,981
* QUADRUPOLE MAGNETS	40,258	57,063	44,517	20,000	26,000
SPEC. DEVICES/SPOOLS	39,420	79,609	71,268	88,900	115,570
SPECIAL MAGNETS/INSERTIONS	15,000	15,000	15,000	15,000	15,000
INSTALLATION & SURVEY	28,088	61,703	42,875	24,471	36,000
TOTAL MAGNET SYSTEMS:	768,866	913,385	895,974	463,547	619,451

Table III-9
Magnet System Cost Comparison Summary
Adjusted Field Level
Adjusted Aperture
FY84 K$

	A	B	D	C	C*
JUSTED PARAMETER VALUES:					
ADJUSTED FIELD LEVEL, T	6.40	5.75	6.40	3.00	3.00
ADJUSTED NUMBER OF DIPOLES:	3,938	12,810	7,875	4,000	8,000
APERTURE, (DIA: A,B,D; GAP: C,C*),CM:	4.00	4.00	4.00	2.54	2.54
FIELD LEVEL/QUANTITY SCALING FACTOR:	.938	.957	.938	1.000	1.000
APERTURE SCALING FACTOR:	1.000	.890	1.000	1.000	1.000
ESCALATION SCALING FACTOR:	1.050	1.050	1.050	1.050	1.050
(* INDICATES ITEMS ADJUSTED)					
GNET SYSTEMS, WBS 1.4.2					
TOOLING	41,497	23,738	41,497	21,810	21,810
DIPOLE MAGNETS	573,837	642,937	646,421	278,350	384,744
QUADRUPOLE MAGNETS	38,341	54,346	42,397	19,048	24,762
SPEC. DEVICES/SPOOLS	37,543	75,818	67,874	84,667	110,067
SPECIAL MAGNETS/INSERTIONS	14,286	14,286	14,286	14,286	14,286
INSTALLATION & SURVEY	26,750	58,765	40,833	23,306	34,286
TOTAL MAGNET SYSTEMS:	732,254	869,890	853,309	441,473	589,953

B. OTHER TECHNICAL SYSTEMS

"Other Technical Systems" is the nomenclature for all other technical components of the SSC main ring apart from the superconducting magnet systems. The same definitions of these systems apply as described in the RDS. These systems with their associated WBS identification (See Table II-2) are as follows:

1.4.2.2	Cryogenics
1.4.2.3	Vacuum
1.4.2.4	Main Power Supplies
1.4.2.5	Correction Element Power Supplies
1.4.2.6	RF System
1.4.2.7	Injection System
1.4.2.8	Abort System
1.4.2.9	Beam Instrumentation
1.4.2.10	Controls
1.4.2.11	Safety Systems

1. The RDS Model

In the RDS there were significant differences in the conceptual design considerations for the category of cryogenics. In particular there were 24 refrigerator stations for Design C(84) and 12 stations for Designs A(84) and B(84). This amounted to a variation in the costs of these systems (~$50M) as indicated in the details of the RDS cost summaries.

Apart from the category of cryogenics, the costs of all other systems listed above (i.e., 1.4.2.3 vacuum through 1.4.2.11 safety systems) were estimated at $97M for Design A(84). This total amount was less than 5% of the total costs of the RDS estimate.

Approximate estimates of the cost variations of these systems were investigated for each magnet style A(84), B(84), and C(84); however since detailed designs did not exist and the cost variations among the three magnet styles appeared relatively small, it was decided to utilized the costs as determined for Design A(84) for the three RDS magnet systems. This decision was consistent with the purpose of the RDS which was to determine the overall technical and economic feasibility of the SSC for the potential magnet systems under consideration at that time. The results are summarized below.

Table III-10
Reference Design Study
Other Technical Systems Costs (FY84 M$)

	A (84)	B (84)	C (84)
1.4.2.2 Cryogenics	123.9	115.9	158.2
1.4.2.3 Vacuum Through 1.4.2.11 Safety Systems	96.8	96.8	96.8
Total Costs	220.7	212.7	255.0

2. The Current Cost Evaluation

The purpose of this report is to specifically evaluate all systems costs that vary with magnet style. In concert with this purpose, the cost of other technical systems has been reviewed for each design style.

A detailed bottoms-up estimate was not done for each design style. In general, the RDS costs for Design A(84) were used as the cost baseline and appropriate components were scaled according to ring size or half-cell length.

For cryogenics, a new detailed estimate was made for Design Style C and D. The cryogenics design for Style C has changed significantly and now also utilizes 12 refrigeration stations.

A brief description of the scaling method is given for each technical system in the next sections. Table III-11 will be used in subsequent sections for systems that scale by the number of half-cells. Table III-11.2 through Table III-11.11 show the adjusted costs for the other technical systems elements. The last decimal digit of the table identification, (Table III-11."xx") corresponds to the last decimal digit of the WBS (1.4.2."xx") identifier for reference. The results are tabulated in Table III-12.

Table III-11
Scaling Factors for Other Technical Systems
(FY84 M$)

	RDS A(84)	A	B	D	C	C*
Field B(T)	6.5	6.4	5.75	6.4	3.0	3.0
Circumference(km)	90	92	100	92	172	172
No. Half Cells	783	792	792	792	1332	1332
Half Cell Scaling Factor	1.0	1.01	1.01	1.01	1.70	1.70
Circumference Scaling Factor	1.0	1.02	1.11	1.02	1.90	1.90

1.4.2.2 Cryogenics Systems

The major components of the cryogenics systems are the refrigerator compressor systems and their associated liquid and gas storage systems, cryogenic piping, and controls. Cryosystems for production magnet testing and special equipment for tunnel magnet testing are also included. The overall costs for these systems for Design D is currently estimated at $136M (FY84$).

As noted above, all magnet design styles now specify systems that utilize the same number of refrigerator stations. Assuming that Design C incorporates an additional 20K pipe for shield cooling and the standard 150% multiplier is applied to all of the designs uniformly, the A.C. power consumption for the various designs will be as follows:

Design Style	A	B	D	C	C*
A.C. Power (MW)	26.2	29.6	32.3	25.1	33.0

Each of the cryogenic systems designs for the above magnet systems are different in conception. For example they have different amounts of liquid storage relative to the total inventory; some have liquid air plants.

The costs for Designs A and B are taken from the RDS. The costs for Designs D and C result from new estimates submitted by the laboratories with adjustments to rectify omissions. The costs for C* is on the same basis as C with compressors and refrigerators scaled according to A.C. power.

The overall costs for each system are presented in Table III-11.2 below. Within this summary, Design C includes a warm gas return header and controls. A production test facility is also included for each system.

Table III-11.2
Cryogenics Systems Cost (FY84 M$)

	RDS A(84)	A	B	D	C	C*
Total	123.9	129	121	136	137	150

1.4.2.3 Vacuum System

The main ring vacuum system costs are in three main subsystems:

a) the warm bore system for the six straight sections
b) the cold beam tube system within the main ring magnets
c) the cryostat insulating vacuum system

The warm bore system is the same for all designs. The cold beam tube system is dominated with equipment that resides at the spool pieces and the costs are proportional to the number of half cells in the main ring. The insulating vacuum category includes a large number of turbo-carts for installation and emergency pumping and valves and gauges proportional to the number of half cells. Thus the insulating vacuum costs will scale as the number of half cells for 2-in-1 designs and 1-in-1 designs will have an additional factor of 2.

Table III-11.3
Vacuum System Cost (FY84 M$)

	RDS A(84)	A	B	D	C	C*
Warm Bore	3.40	3.40	3.40	3.40	3.40	3.40
Cold Bore (scaling)	4.24	4.28 (1.01)	4.28 (1.01)	4.28 (1.01)	7.20 (1.70)	7.20 (1.70)
Cryostat (scaling)	4.58	4.62 (1.01)	9.25 (2.02)	9.25 (2.02)	7.80 (1.70)	15.60 (3.40)
Total	12.22	12.30	16.93	16.93	18.40	26.20

1.4.2.4 Main Power Supplies

The power supply systems for the various magnet types are not directly comparable. Designs A, B, and D have the same design that is similar to the design described in the RDS. Design C is considerably more complicated, with four main supplies per aperture, and per sector. The additional cost is somewhat compensated for by a reduction to four power supply sectors in Design C and C*. This appears feasible due to the lower inductance of the type C magnet, although voltages during quench or dump and ramp rate limitations must be considered carefully.

The power supply systems have been analyzed in four subsystems:

1. Power Supplies
2. Energy Extraction: Dump resistors and switches.
3. Quench protection: An analysis for the RDS indicated that a passive scheme with one diode per magnet would cost about the same as an active scheme with one heater per half cell. The type C design has four diode packs per half cell, which is equivalent. We believe this subsystem is comparable in cost to the system evaluated in the RDS.
4. Software.

The results of the analysis are provided in the following table.

Table III-11.4
Main Power Supply Cost
(FY84 M$)

	RDS A(84)	A	B	D	C	C*
Power Supplies	9.9	9.9	9.9	9.9	11.1	11.1
Energy Extr.	3.4	3.4	3.4	3.4	3.4	3.4
Quench Prot.	6.4	6.4	6.4	6.4	6.4	6.4
Software	1.3	1.3	1.3	1.3	1.3	1.3
Total	21.0	21.0	21.0	21.0	22.2	22.2

The overall difference of $1.2M is considered smaller than the uncertainty in the estimate. The RDS total estimate of $21.0M is therefore used for all magnet design styles in the summary Table III-12.

1.4.2.5 Correction Element Power Supplies and Quench Protection

The power supply sub-systems of this category include the following:

1. Correction Dipole Elements
2. Higher Order Elements
3. Matching Sextupole Corrections
4. Persistent Current Correction

In the RDS, 900 dipole corrector power supplies were assumed for 783 half cells. The difference, i.e., 117 units, were used at special locations such as straight sections. The 783 units will scale as the number of half cells.

For higher order elements, the RDS assumed 24 circuits per aperture per correction type. These are the same for all designs.

The matching section sextupoles are no longer needed. The persistent current correctors are not required for C or C*; the same costs should apply for A, B, and D as described in the RDS.

Table III-11.5

Correction Element Power Supply Costs

(FY84 M$)

	RDS A(84)	A	B	D	C	C*
Dipole half-cell corr.	7.40	7.50	7.50	7.50	12.60	12.60
(scaling)		(1.01)	(1.01)	(1.01)	(1.70)	(1.70)
Misc. Dipole corr.	1.10	1.10	1.10	1.10	1.10	1.10
High Order Elements	2.06	2.06	2.06	2.06	2.06	2.06
Matching Sextupoles	2.24	0	0	0	0	0
Persistent Current	.58	.58	.58	.58	0	0
Total	13.37	11.24	11.24	11.24	15.76	15.76

1.4.2.6. Radio Frequency System

The voltage required for the rf system is determined by the following:

1. The amount of voltage required to accelerate to full energy in 1,000 seconds. This implies a factor of ~2 more voltage for the Design C ring by the reduced revolution frequency (20 MV for A and D and 40 MV for C and C*).
2. The stability of the beam against coupled bunch oscillation modes. Preliminary studies from the SSC Task Force on Operations and Commissioning indicate that Design C will require 80 MV at injection to provide the larger momentum spread required for stability. This is eight times the required voltage for the higher field Designs A, B, and D.

Since Designs A and D require 20 MV for acceleration, the 80 MV required for stability will increase the rf costs by a factor of 4 for the Designs C and C*.

Table III-11.6
Radiofrequency Costs
(FY84 M$)

	RDS A(84)	A	B	D	C	C*
Total	7.73	7.7	9.3	7.7	30.9	30.9

1.4.2.7 Injection System

There is no significant difference in the injection costs for the various designs. The estimated cost is $2.94 M.

It should be pointed out the the bending magnets in the injection straight sections are for two purposes:

a. to reduce accidental losses in the superconducting magnets.

b. to separate the beams sufficiently to insert kicker magnets.

If the protection against accidental loss is not necessary, then there would be a cost difference between 1-in-1 and 2-in-1 designs.

1.4.2.8 The Abort System

The main considerations for the abort system are the increased beam levels and slower revolution frequency of the low field designs. This will increase the cost of the beam dump and the kicker magnets and their associated power supplies as follows:

Table III-11.8
Abort System Costs
(FY84 M$)

	RDS A(84)	A	B	D	C	C*
Beam Dump and Pulsed Magnet (scaling)	3.35	3.38 (1.01)	3.38 (1.01)	3.38 (1.01)	5.69 (1.70)	5.69 (1.70)
Other Components	4.67	4.67	4.67	4.67	4.67	4.67
Total	8.02	8.10	8.10	8.10	10.40	10.40

1.4.2.9 Beam Instrumentation

Most of the cost of beam instrumentation is in the beam position detectors. All of the costs of these units except for the software and electronics development will scale as the number of half cells.

The radiation detectors will also scale as the number of half cells except for those required for special locations (~20%). We assume that wire scanners and other special devices do not scale with the number of cells. The results are summarized below.

Table III-11.9
Beam Instrumentation Costs
(FY84 M$)

	RDS A(84)	A	B	D	C	C*
Scaled elements	4.74	4.79	4.79	4.79	8.06	8.06
(scaling factor)		(1.01)	(1.01)	(1.01)	(1.70)	(1.70)
Other elements	2.26	2.26	2.26	2.26	2.26	2.26
Total	7.0	7.05	7.05	7.05	10.32	10.32

1.4.2.10 Controls

The control system is composed of the following elements:

1. Host computer
2. Control consoles
3. Sector computers
4. Microprocessors
5. Interface crates and controllers
6. Software
7. Ring information network

The host computer, consoles, sector computers and software do not scale with magnet design. The micro-processor units, interface crates and controllers will scale by the number of half cells. The ring information network will scale as the ring circumference. The results are tabulated below.

Table III-11.10
Controls
(FY84 M$)

	RDS A(84)	A	B	D	C	C*
Micro-pro, crates, controllers	4.89	4.94	4.94	4.94	8.31	8.31
(scale)		(1.01)	(1.01)	(1.01)	(1.70)	(1.70)
Ring information network	1.29	1.32	1.43	1.32	2.45	2.45
(scale)		(1.02)	(1.11)	(1.02)	(1.90)	(1.90)
All other systems	13.10	13.10	13.10	13.10	13.10	13.10
Total	19.28	19.36	19.47	19.36	23.86	23.86

1.4.2.11 Personnel Protection System

This personnel protection system consists of monitors, controls, and equipment that are associated with the various entrance and access points around the main ring. While the precise rules for access spacing are not well established, we have assumed that the number of access regions will scale as the size of the ring mainly due to safety considerations.

Table III-11.11
Personnel Protection System Costs
(FY84 M$)

	RDS A(84)	A	B	D	C	C*
Personnel Protection	5.32	5.43	5.90	5.43	10.11	10.11
(scaling)		(1.02)	(1.11)	(1.02)	(1.90)	(1.90)

1.4.2.2 through 1.4.2.11 Cost Summary of Other Technical Systems

The results of the previous ten subsections are summarized below in Table III-12. The first column shows the 1984 RDS estimate for comparison. All costs are expressed in FY1984M$.

Table III-12

Other Technical Systems Cost Summary

(FY84 M$)

(WBS) 1.4.2.	STYLE:	RDS A(84)	A	B	D	C	C*
2	CRYOGENICS	123.9	129.0	121.0	136.0	137.0	150.0
3	VACUUM SYSTEMS	12.2	12.3	16.9	16.9	18.4	26.2
4	MAIN POWER SUPPLIES	21.0	21.0	21.0	21.0	21.0	21.0
5	CORRECTION POWER SUPPLIES	13.4	11.2	11.2	11.2	15.8	15.8
6	RF SYSTEM	7.7	7.7	9.3	7.7	30.9	30.9
7	INJECTION SYSTEM	2.9	2.9	2.9	2.9	2.9	2.9
8	ABORT SYSTEM	8.0	8.1	8.1	8.1	10.4	10.4
9	INSTRUMENTATION	7.0	7.0	7.0	7.0	10.3	10.3
10	CONTROLS	19.3	19.4	19.5	19.4	23.9	23.9
11	SAFETY SYSTEMS	5.3	5.4	5.9	5.4	10.1	10.1
	TOTAL "OTHER" TECH SYS COST	220.7	224.1	222.9	235.7	280.6	301.4

C. Conventional Systems Costs and Analysis

In order to provide a reasonable basis for conventional systems costs in the RDS, a median site was created by utilizing main ring sectors taken from four differing geological regions (see Fig. 1). This method allowed for the development of representative cost estimates for tunneling in the absence of a specific site, and served to illustrate tunneling techniques customarily employed for each of the various types of conditions. It was envisioned that segments of the tunnels were cut through hard rock (igneous, limestone, or hard sandstone), through soft clayey silt with sand and gravel, and through areas where the land had first been excavated, the tunnel constructed and then covered with soil. Precast concrete pipe, cast-in-place concrete liners, or segmented precast concrete liners were used, as appropriate. Figure 2 illustrates the variation in surface elevation of the various geological sectors of the median site. The median site was developed for the 6.5T RDS-A(84) magnet design. The method of extending the median site to other sizes is described in Section C-2.

1. "Median Site" in the Reference Designs Study

The north geological sector in the 56 mile ring in the RDS extends for 17 miles and varies from an elevation of 922 ft at mile 11.6 to 831 ft at mile 22. The beam dump is at mile 18.6, at depth of 30 ft, and collision hall 2 is at the eastern end of this sector at a depth of 17 ft. Surface deposits in this sector are sandy, silty clay to a depth of 10 ft, with some boulders up to 1.5 ft diameter. Layers of soft and hard rock can be found in this sector. Rock tunneling (Type I) is needed for the first 12 miles. This is bored with a machine and lined with shotcrete reinforced with welded wire fabric. Cut-and-cover tunneling in soft shale is needed in the last 5 miles of this sector and precast concrete pipe is used for this portion of tunnel.

The east sector extends for 13 miles and consists of sand and clayey silt near the surface, with sand and gravel increasing with depth. Surface elevation varies from 900 to 832 ft and, at collision hall 4, the surface elevation is 880 ft. Soft ground tunneling (type II) is assumed for this area, and the tunnel is formed from a precast segmented concrete lining.

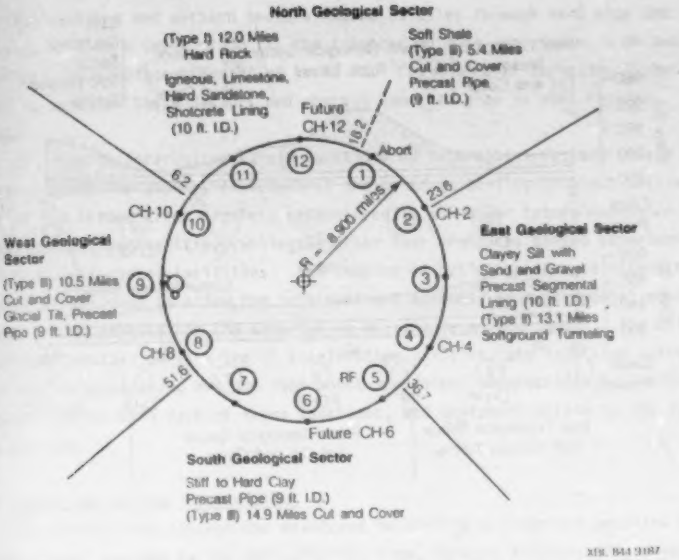
North Geological Sector
(Type I) 12.0 Miles
Hard Rock
Igneous, Limestone,
Hard Sandstone,
Shotcrete Lining
(10 ft. I.D.)
Soft Shale
(Type III) 5.4 Miles
Cut and Cover
Precast Pipe
(9 ft. I.D.)
Future
CH-12
18.2
Abort
12
11
1
6.2
23.6
R = 8,900 miles
CH-10
10
2
CH-2
East Geological Sector
Clayey Silt with
Sand and Gravel
Precast Segmental
Lining (10 ft. I.D.)
(Type II) 13.1 Miles
Softground Tunneling
West Geological
Sector
(Type III) 10.5 Miles
Cut and Cover
Glacial Till, Precast
Pipe (9 ft. I.D.)
9
3
8
4
CH-8
CH-4
51.6
7
RF
5
36.7
6
Future CH-6
South Geological Sector
Stiff to Hard Clay
Precast Pipe (9 ft. I.D.)
(Type III) 14.9 Miles Cut and Cover
XBL 844-3187

Fig. 1. The SSC main ring tunnel types in relation to the four hypothetical geological sectors and their composition. Mileage around the perimeter, clock position and the position of each collision hall are also indicated for a ring of 56 miles circumference.

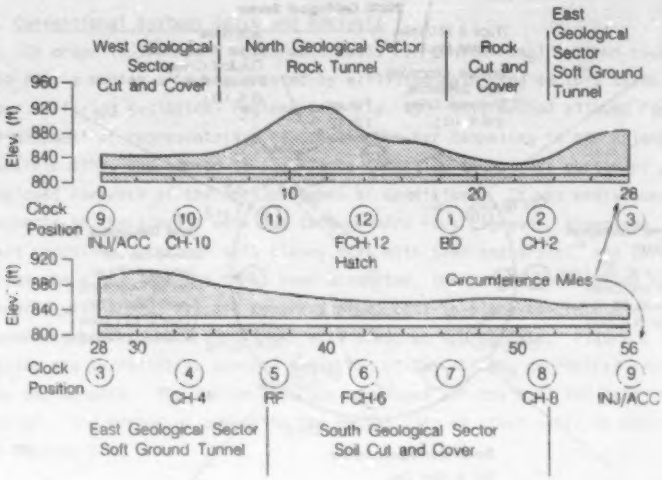
West Geological Sector Cut and Cover
North Geological Sector Rock Tunnel
Rock Cut and Cover
East Geological Sector Soft Ground Tunnel
960
920
880
840
800
Elev. (ft)
0
10
20
28
Clock Position
9
10
11
12
1
2
3
INJ/ACC
CH-10
FCH-12 Hatch
BD
CH-2
Circumference Miles
920
880
840
800
Elev. (ft)
28
30
40
50
56
Clock Position
3
4
5
6
7
8
9
CH-4
RF
FCH-6
CH-8
INJ/ACC
East Geological Sector Soft Ground Tunnel
South Geological Sector Soil Cut and Cover

Fig. 2. Profile of assumed surface topography around the circumference of the main ring tunnel indicating the relationship between circumferential distance in miles and clock position and their joint relationship to main geological features and tunnel construction methods. Positions of the collision halls, rf acceleration section, injection to the SSC main ring, and beam dump are given to illustrate the nature of the overlying strata at these points (and thus assumed elevations). These features impact on construction costs and methods.

The southern and western sectors extend 25 miles through hard clay and glacial till to a depth of 50 ft; the trenches in soil are stable, with near-vertical cut slopes, at depths up to 60 ft. Cut-and-cover tunneling (type III) is used for these sectors and precast concrete pipe is used for the tunnel.

The ring is interrupted at six locations by interaction regions (where the beams collide for physics experiments) and by three utility straight sections. Two of the former areas are left undeveloped to allow for future expansion of experimental opportunities, while the other four are sites of the experimental halls and associated facilities. The complex of buildings at each interaction region is designed to allow the transport and assembly of experimental equipment, and to provide for the undertaking of long-term experiments. The utility straight sections contain the rf accelerating cavities, the injection system for the incoming beam, and the beam abort apparatus. Appropriate buildings are associated with each of these functions, and equipment access to the tunnel is provided.

2. Extension of the "Median Site"

The Median Site concept was developed to provide a technical baseline for conventional systems in the RDS. The A/E firm, Parsons Brinckerhoff, prepared this model so that civil, structural, electrical and mechanical engineers could do a design study under "almost realistic" conditions. As described earlier, the model was done for a 56 mile ring, employing 6.5T magnets, and extended to larger circumferences as required by the utilization of lower field magnets.

In order to illustrate how the median site can be extended, another illustration has been created. Assuming that the same proportions of geological conditions prevail, Figure 3 shows how the varying segments might appear. The length of such segments are shown as in Table III-13.

CONDITIONS:

GEOLOGICAL SECTOR		MATERIAL	METHOD
North	Type I	Hard Rock Igneous, Limestone Hard Sandstone	Shotcrete Lining (10 ft. I.D.)
North	Type II	Soft Shale	Cut & Cover Precast Pipe (9 ft. I.D.)
East	Type I	Clayey Silt with Sand & Gravel	Precast Segmental Lining, Softground Tunneling (10 ft. I.D.)
South	Type III	Stiff to Hard Clay	Cut & Cover Precast Pipe (9 ft. I.D.)
West	Type III	Glacial Till	Cut & Cover Precast Pipe (9 ft. I.D.)

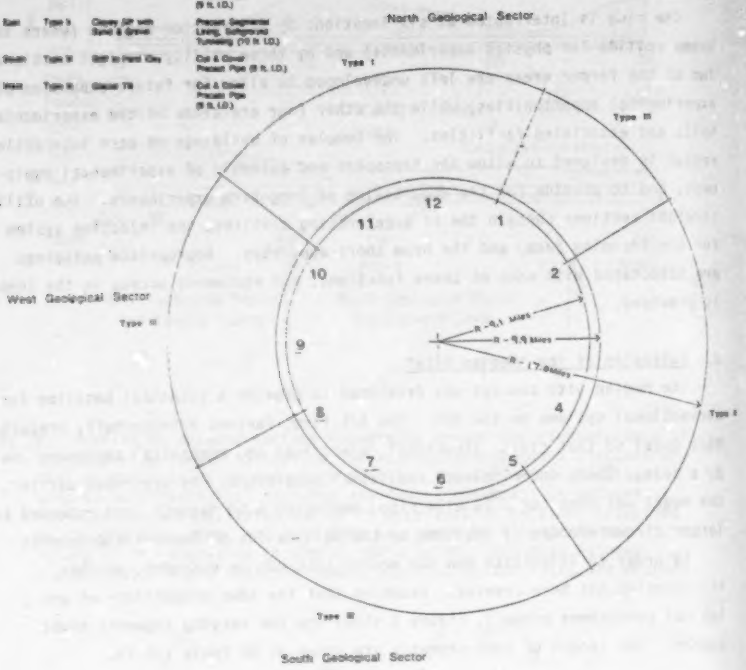
North Geological Sector
Type I
Type III
West Geological Sector
Type III
Type I
Type III
South Geological Sector
12
1
2
4
5
6
7
8
9
10
11
R - 9.1 Miles
R - 9.9 Miles
R - 17.0 Miles

Fig. 3. Extension of Median Site Concept to Three Ring Sizes.

Table III-13
Length of Typical Tunnel Segments
(feet)

-Design Style	A, D	B	C, C*
Type I	64,806	70,442	121,160
Type II	70,722	76,872	132,220
Type III	166,317	180,779	310,940
	301,845	328,093	564,320
Circumference (miles)	57	62	107

3. Technical Considerations

In the RDS, a 9 or 10 ft internal diameter tunnel is assumed to lie in a horizontal plane at an average depth of 40 ft below the surface. The superconducting magnets and other beam handling devices are positioned and aligned in the tunnel. Vacuum pipes, cryogenic systems, power supplies, and instrumentation services must be provided. Space in the tunnel must also be allowed for suitable personnel and equipment transporters. In addition, adequate aisle space must be provided for the people who will work on technical components in the tunnel.

Recent work at the CDG has examined two tunnel cross sections. The arrangement of equipment, piping, magnets, transporters and working space can be seen in Figs. 4 and 5. The tunnel shell in the example is shotcrete lined, with welded wire fabric reinforcement, typical of hard-rock tunneling construction. A poured concrete floor results in a level, 8.3 ft wide working surface within a 9-10 foot circular cross section. Floor drainage is installed. Lighting fixtures and a cable tray are anchored in the roof and conduit racks are fixed to the wall on the magnet side of the tunnel. These last items support lines for compressed gas, 480 V electrical cable, water supply and return lines, and a warm-helium gas return line. Periodically a signal area containing a telephone, signaling system, fire pull alarm, and space for monitoring instrumentation is located on the wall.

Normal and purging ventilation are provided, complete with the necessary fans, ducts, outlets and controls. Ventilation is an important feature in the tunnel due both to its length and because of the large numbers of people working at a variety of activities during the construction phase. An

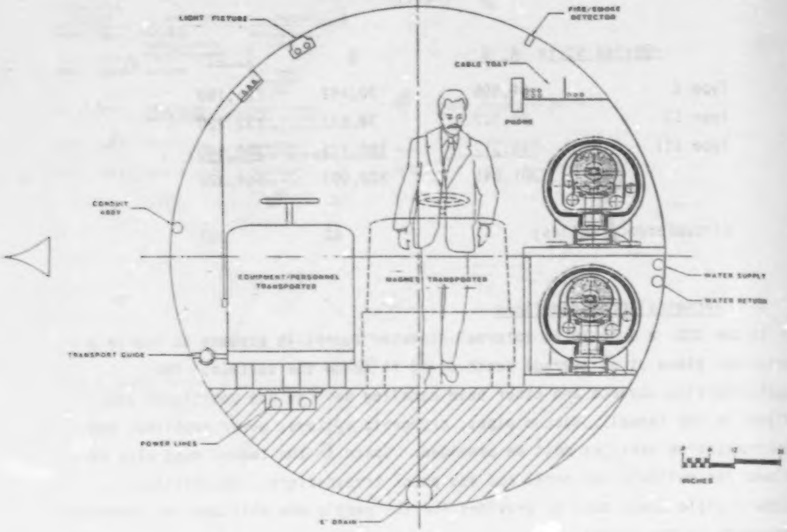
LIGHT FIXTURE
FIRE/SMOKE DETECTOR
CABLE TRAY
PHONE
CONDUIT ASSY
COMPONENT/PERSONNEL TRANSPORTER
MAGNET TRANSPORTER
WATER SUPPLY
WATER RETURN
TRANSPORT GUIDE
POWER LINES
INCHES
6" DRAIN
TUNNEL CROSS SECTION

Fig. 4. Tunnel Cross Section Magnet Design D

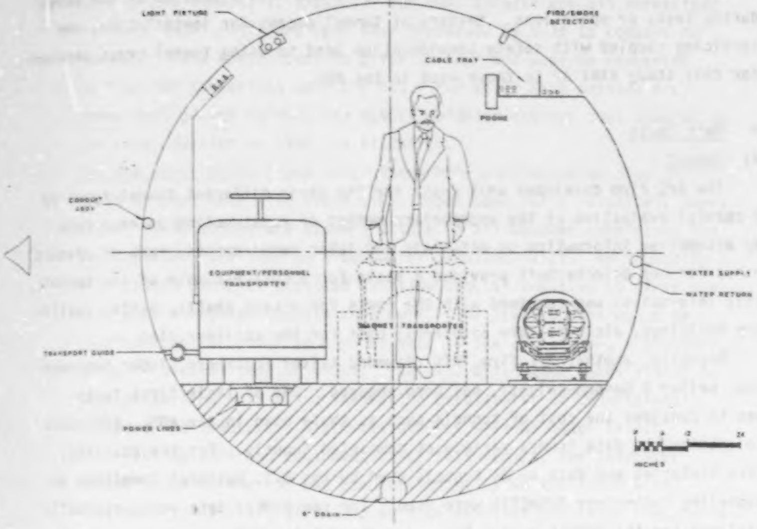
LIGHT FIXTURE
FIRE/SMOKE DETECTOR
CABLE TRAY
PHONE
CONDUIT ASSY
EQUIPMENT/PERSONNEL TRANSPORTER
WATER SUPPLY
WATER RETURN
MAGNET TRANSPORTER
TRANSPORT GUIDE
POWER LINES
0 6 12 24
INCHES
6" DRAIN

Fig. 5. Tunnel Cross Section Magnet Design C

additional need for the ventilation is to replenish the atmosphere quickly if a large volume of helium were accidentally vented into a section of the tunnel during tests or operations. Matters of tunnel access for installation, and servicing coupled with safety consideration lead to using tunnel cross sections for this study similar to those used in the RDS.

4. Unit Costs

A) Tunnel

The A/E firm developed unit costs for the three different tunnel types by a careful evaluation of the appropriate method of construction in each case. By assembling information on materials and labor requirements, rate of advance, etc., Parsons Brinckerhoff provided a basis for a cost estimate of the tunnels. This information was combined with the costs for access shafts, exits, auxiliary buildings, etc., to form an overall cost for the collider ring.

Recently, another A/E firm, RTK (Raymond Kaiser Engineers, Tudor Engineering, Keller & Gannon-Knight), has been engaged. One of their first tasks was to consider the cost of tunnels such as those used in the RDS. RTK chose to examine the data from a variety of completed tunnels. For the analysis, case histories and data on 84 tunnels used by the U.S. National Committee on Tunneling Technology (USNCTT) were used. The raw USNCTT data were originally analyzed for the USNCTT by Don Rose, a member of the RTK team. The USNCTT data are drawn nationwide and represent a recent study published in June, 1985. The USNCTT cost data have been normalized and are the final as-built cost including all paid claims and change orders.

a. Hard Rock Tunnels (Type I). The USNCTT weighted average cost for hard rock tunnels excavated by tunnel boring machines (TBM's) is $323/CY. The USNCTT costs are all normalized to July, 1982, costs and have been increased by 3.7% to compare to 1984 costs used in the RDS. This USNCTT cost is given in $/CY and must be converted to $/LF for comparison with the RDS. For an 11-foot outside diameter hard rock TMB tunnel, the USNCTT weighted average cost, updated to the first quarter of 1984, is $1180/LF.

b. Soft Ground Tunnels (Type II) The USNCTT weighted average cost for soft ground tunnels is $300/CY. The USNCTT costs are all normalized to July, 1982, costs and have been increased by 3.7% to compare to the RDS. This USNCTT cost is given in $/CY and must be converted to $/LF for comparison with the RDS. For an 11-foot outside diameter soft ground tunnel, the USNCTT weighted average cost updated to the first quarter of 1984, is $1,095/LF.

c. Cut and Cover Costs (Type III) The scheme considered an open cut about 45 feet deep with steep side slopes open for a relatively short time. These slopes are assumed stable in all weather conditions the year around, provided no groundwater problems exist. An unusually wide bottom width is provided to allow special vehicles to carry precast pipe alongside the finished work. The precast pipe would be carried from the plant to a point near to the excavation, a distance of up to several tens of miles. The excavation work lends itself to mass production work using innovative excavators, or conventional scrapers and tractors. Different bidders will no doubt select different methods and equipment. For this report, the cut/cover scheme shown in the RDS has been evaluated by an RTK study with reference to federal, state and private agencies for costs comparable of work done using conventional equipment. RTK believes the cut/cover tunnel will cost $873/LF (first quarter 1984 prices) for the example studied. The average cost for all cut and cover costs (Type III) described is estimated as $780/LF.

d. Summary The recent evaluation by RTK can be conveniently compared to the earlier work by looking at Table III-14. There is excellent agreement between these independent estimates by experienced A/E firms.

Table III-14
Unit Cost Estimates for Tunnel Types
($ Per Linear Foot)

	RDS	RTK	CDG Value
Main Ring Tunnel - Type I	1,150	1,167; 1,180	1,160
Main Ring Tunnel - Type II	1,100	1,095	1,100
Main Ring Tunnel - Type III, avg	755	780	770
Weighted Avg., Types I, II, III	920	-	930

The total Conventional Facility costs for the Collider Ring WBS 1.4.1 are shown for the five designs in Table III-15.

B) Ramps/Slots

There are several differences that arise from the choice of magnetic field and corresponding style of magnet. The different circumferences have been addressed earlier, although there are additional items that must be considered. First of all, the allowance for site infrastructure (such as roads, utilities) must scale with the circumference. In addition, the number of exits will be increased in proportion to the increased tunnel length, thereby keeping fixed the distance between exits within the tunnel.

In contrast to the position taken during the RDS, the same number of refrigerator/compressors stations (12) will be used in all the configurations. This will change the distance between stations from 5 miles in Design A to almost 9 miles in Design C.

Because it is envisioned that the very long superferric magnets will be assembled at four places adjacent to the collider ring, a number of adjustments must be made to the plan for a campus works area, and to the approach used for getting the 380 ft magnets into the ring. One might expect to need more works building space due to the assembly areas being dispersed.

The predominant effect of the long magnets is to require access ramps or slots at four locations to move assembled magnets down into

Table III-15
Conventional Facility Cost Comparison Summary
(FY 84K$)

MAGNET STYLE:	A	B	D	C	C*
PARAMETER VALUES:					
FIELD LEVEL, T	6.40	5.75	6.40	3.00	3.00
CIRCUMFERENCE, MI	57.17	62.14	57.17	106.88	106.88
(CIRCUMFERENCE, KM)	92.00	100.00	92.00	172.00	172.00
CONVENTIONAL FACIL. SYSTEMS,					
.1 LAND IMPROVEMENTS	15,300	16,631	15,300	28,605	28,605
.2.1 TUNNEL TYPE I	88,038	95,693	88,038	164,592	164,592
.2.2 TUNNEL TYPE II	90,249	98,097	90,249	168,726	168,726
.2.3 TUNNEL TYPE III	154,292	167,709	154,292	288,459	288,459
.2.4 TUNNEL (OTHER ELEMENTS) (CRYO. BM DUMP, RF, ETC)	13,927	13,927	13,927	13,927	13,927
.3 CRYOGENIC FACILITIES	7,998	7,998	7,998	7,998	7,998
.4 SUPPORT BUILDINGS	1,750	1,902	1,750	3,272	3,272
.5 UTILITIES	38,822	42,198	38,822	72,581	72,581
.6 ACCESS SHAFTS	0	0	0	13,540	13,540
TOTAL CONVEN. FACILITIES	410,376	444,154	410,376	761,700	761,700

the tunnel. RTK has done a study of this approach using a depth appropriate for soft ground tunnels. In FY84 dollars they have established a cost of $5.7M each for a ramp scheme and $3.4M each for a vertical slot scheme.

D. Systems Engineering

The Systems Engineering (EDI for Technical Systems and AE/CM for the Conventional Facilities) are described below for the Magnet Systems, Other Technical Systems, and Conventional Facilities.

1. Magnet Systems

During the RDS cost estimate analysis, a very thorough and careful development of the Engineering, Design, and Inspection tasks and costs was done for the dipole magnet systems. Although a special case, the main ring magnet system - by far the largest technical subsystem - is not without precedent. The Tevatron magnet design and fabrication is a useful model for this undertaking; in fact, the basic principles and mechanical structure of the SSC designs closely follow those of the Tevatron magnet system. The number of units - about 4,000 in the SSC Reference Design A case - is not vastly different than that for the Tevatron, which had approximately 1,000 dipole magnets. Furthermore, an adequate R&D program prior to the SSC construction phase is assumed. One result of this R&D phase will be the production of a significant number of magnets made with full-scale tooling, i.e., the same tooling as will be used in the first production. Thus, it is assumed herein that, at the start of construction, the bulk of the tooling and manufacturing methods will be well worked out and needs for inspection manpower will be minimized by careful planning and use of specialized tooling and analysis equipment. These assumed conditions applied in many ways to the construction stage of the Tevatron, so the magnet production, testing and installation phase of the Tevatron can be used as a model for estimating tne design costs.

In the RDS, a manpower analysis was made for the Tevatron experience according to the following tasks:

Engineering
Design and Drafting
Liaison (shops, manufacturers, vendors, etc.)

Inspection, testing and monitoring
Quality assurance
Documentation
Office and staff support

Appropriate improvements or modifications were made to the Tevatron manpower levels as suggested by their experience. These manpower levels were then extrapolated to the scale of the SSC project. The resulting total level of effort was then represented as a percentage of the total dipole magnet construction cost (10% for EDI resulted). For the current comparison study, the same EDI value (10%) is used for the dipole and quadrupole construction, and values of 15, 20, 25, and 20% are used respectively for magnet tooling, special devices/spools, special magnets/insertions, and installation respectively.

The overall percentage values used for each of the various magnet designs, and the resulting EDI costs for the construction program are tabulated in Table III-16. The net effective weighted average EDI percentage for Magnet Systems is indicated at the last line of the table.

Table III-16
Magnet Systems EDI
(FY84 K$)

(WBS) 1.4.2.1.	STYLE: EDI	A	PCT	B	PCT	D	PCT	C	PCT	C*	PCT
1	TOOLING	41,497	15	23,738	15	41,497	15	21,810	15	21,810	15
2	DIPOLE MAGNETS	573,837	10	642,937	10	646,421	10	270,350	10	384,744	10
3	QUADRUPOLE MAGNETS	38,341	10	54,346	10	42,397	10	19,840	10	24,762	10
4	SPEC. DEVICES/SPOOLS	37,543	20	75,818	20	67,874	20	84,667	20	110,067	20
5	SPEC. MAGNETS/INSERTIONS	14,286	25	14,286	25	14,286	25	14,286	25	14,286	25
6	INSTALLATION & SURVEY	26,750	20	58,765	20	40,833	20	23,306	20	34,286	20
	TOTAL ADJUSTED MAG SYS	732,254		869,890		853,309		441,473		589,953	

1.4.2.1. EDI COSTS

1	TOOLING	6224.6	3560.7	6224.6	3271.4	3271.4
2	DIPOLE MAGNETS	57383.7	64293.7	64642.1	27035.0	38474.4
3	QUADRUPOLE MAGNETS	3834.1	5434.6	4239.7	1984.0	2476.2
4	SPEC. DEVICES/SPOOLS	7508.6	15163.7	13574.8	16933.3	22013.3
5	SPEC. MAGNETS/INSERTIONS	3571.4	3571.4	3571.4	3571.4	3571.4
6	INSTALLATION & SURVEY	5350.0	11753.0	8166.6	4661.1	6857.1
	TOTAL EDI COST:	83872.4	103777.2	100419.3	58177.9	76663.9
	OVERALL EDI PERCENTAGE:	11.5	11.9	11.8	13.2	13.0

2. Other Technical Systems

The general design of the SSC closely resembles large accelerator systems now in existence. Many of the components and subsystems required for the SSC are very similar to existing components and subsystems. For example, the radio-frequency system for the SSC main ring is currently visualized as the same system used for the PEP collider ring except that only about 2/3 of the rf cavities are required for most of the SSC designs under consideration. Apart from magnets and cryogenics, the specifications for most systems are sufficiently understood that the EDI can be estimated with confidence based on past experience.

Experience from other relatively large accelerator projects (PEP & Tevatron) indicates that the EDI for technical components is ~25% of construction costs. This should be compared with EDI rates of all SSC systems (except magnets and cryogenics) which average 24% for the SSC. Because of their considerably larger cost scale, the magnet systems EDI are expected to have a lower percentage of construction cost as shown by the analysis in the preceeding section. The cryogenics EDI of 15% reflects an average of two components: a large refrigerator purchase (~$60M) for which designs exist and associated cryogenic systems which have an estimated EDI of ~25%.

A summary of the resulting estimated EDI for other technical systems of the SSC is provided in Table III-17.

Table III-17
Other Technical Systems EDI
(FY84 M$)

(WBS)	STYLE: EDI	A	PCT	B	PCT	B	PCT	C	PCT	C*	PCT
1.4.2.	**CONSTRUCTION COSTS:**										
2	CRYOGENICS	129.0	15	121.0	15	136.0	15	137.0	15	150.0	15
3	VACUUM SYSTEMS	12.3	25	16.9	25	16.9	25	18.4	25	26.2	25
4	MAIN POWER SUPPLIES	21.0	20	21.0	20	21.0	20	21.0	20	21.0	20
5	CORRECTION POWER SUPPLIES	11.2	20	11.2	20	11.2	20	15.8	20	15.8	20
6	RF SYSTEM	7.7	25	9.3	25	7.7	25	30.9	25	30.9	25
7	INJECTION SYSTEM	2.9	25	2.9	25	2.9	25	2.9	25	2.9	25
8	ABORT SYSTEM	8.1	25	8.1	25	8.1	25	10.4	25	10.4	25
9	INSTRUMENTATION	7.0	25	7.0	25	7.0	25	10.3	25	10.3	25
10	CONTROLS	19.4	30	19.5	30	19.4	30	23.9	30	23.9	30
11	SAFETY SYSTEMS	5.4	25	5.9	25	5.4	25	10.1	25	10.1	25
	TOTAL "OTHER" TECH SYSTEMS COSTS:	224.1		222.9		235.7		280.6		301.4	
1.4.2.	**EDI COSTS:**										
2	CRYOGENICS	19.4		18.1		20.4		20.6		22.5	
3	VACUUM SYSTEMS	3.1		4.2		4.2		4.6		6.5	
4	MAIN POWER SUPPLIES	4.2		4.2		4.2		4.2		4.2	
5	CORRECTION POWER SUPPLIES	2.2		2.2		2.2		3.2		3.2	
6	RF SYSTEM	1.9		2.3		1.9		7.7		7.7	
7	INJECTION SYSTEM	.7		.7		.7		.7		.7	
8	ABORT SYSTEM	2.0		2.0		2.0		2.6		2.6	
9	INSTRUMENTATION	1.8		1.8		1.8		2.6		2.6	
10	CONTROLS	5.8		5.8		5.8		7.2		7.2	
11	SAFETY SYSTEMS	1.4		1.5		1.4		2.5		2.5	
	TOTAL "OTHER" TECH SYS	42.5		43.0		44.7		55.8		59.7	
	OVERALL EDI PERCENTAGE:	19.0		19.3		19.0		19.9		19.8	

3. Conventional Systems

The AE/CM services for the SSC Conventional Systems in the Reference Designs Study were estimated by the AE/CM firm of Parsons Brinckerhoff (PB). Specifically the AE/CM services included:

Project Management and coordination
Quality Assurance/Control
Site Manager
Project Administration
Reporting
Cost and Schedule Control
Contract Administration
Title I Design and Report
Title II Design
Coordination with Technical Facilities Interface
Inspection and Record Keeping
Construction Management and Administration
Construction Safety and Security
Systems Operational Manuals

In the RDS, an across-the-board estimate of 16.0% of construction was developed to cover the AE/CM services listed above independent of ring size.

Discussions were held concerning the possible variation of the AE/CM percentage with ring size in view of the repetitive nature of the design elements for the collider tunnel. An alternative perspective is that there are many nuances in underground construction that require continuous design attention. In particular without detailed site specific information it would not be prudent to assume a reduced AE percentage.

For this study the AE/CM estimate is determined by the same percentage of construction (16%) as developed for the RDS. Table III-18 shows the AE/CM costs for each of the major systems of the conventional facilities.

Table III-18
Conventional Systems AE/CM (ED1A)
(FY84 K$)

STYLE:	A		B		D		C		C*	
AE/CM PERCENT:		PCT		PCT		PCT		PCT		PCT
PARAMETER VALUES:										
FIELD LEVEL, T	6.40		5.75		6.40		3.00		3.00	
CIRCUMFERENCE, MI	57.17		62.14		57.17		106.88		106.88	
(CIRCUMFERENCE, KM)	92.00		100.00		92.00		172.00		172.00	
(WBS)										
1.4.1 CONVENTIONAL FACIL. SYSTEMS, COSTS:										
.1 LAND IMPROVEMENTS	15,300	16	16,631	16	15,300	16	28,605	16	28,605	16
.2.1 TUNNEL TYPE I	88,038	16	95,693	16	88,038	16	164,592	16	164,592	16
.2.2 TUNNEL TYPE II	90,249	16	98,097	16	90,249	16	168,726	16	168,726	16
.2.3 TUNNEL TYPE III	154,292	16	167,709	16	154,292	16	288,459	16	288,459	16
.2.4 TUNNEL (OTHER ELEMENTS) (CRYO, BM DUMP, RF, ETC)	13,927	16	13,927	16	13,927	16	13,927	16	13,927	16
.3 CRYOGENIC FACILITIES	7,998	16	7,998	16	7,998	16	7,998	16	7,998	16
.4 SUPPORT BUILDINGS	1,750	16	1,902	16	1,750	16	3,272	16	3,272	16
.5 UTILITIES	38,822	16	42,198	16	38,822	16	72,581	16	72,581	16
.6 ACCESS SHAFTS	0	16	0	16	0	16	13,540	16	13,540	16
TOTAL CONVEN. FACILITIES	410,376		444,154		410,376		761,700		761,700	
AE/CM COSTS:										
.1 LAND IMPROVEMENTS	2,448		2,661		2,448		4,577		4,577	
.2.1 TUNNEL TYPE I	14,086		15,311		14,086		26,335		26,335	
.2.2 TUNNEL TYPE II	14,440		15,695		14,440		26,996		26,996	
.2.3 TUNNEL TYPE III	24,687		26,833		24,687		46,153		46,153	
.2.4 TUNNEL (OTHER ELEMENTS) (CRYO, BM DUMP, RF, ETC)	2,228		2,228		2,228		2,228		2,228	
.3 CRYOGENIC FACILITIES	1,280		1,280		1,280		1,280		1,280	
.4 SUPPORT BUILDINGS	280		304		280		524		524	
.5 UTILITIES	6,212		6,752		6,212		11,613		11,613	
.6 ACCESS SHAFTS	0		0		0		2,166		2,166	
TOTAL AE/CM COSTS	65,660		71,065		65,660		121,872		121,872	
OVERALL AE/CM PERCENTAGE:	16.0		16.0		16.0		16.0		16.0	

E. Contingency Analysis

1. Magnet Systems

The following contingencies were estimated for the magnet Design Styles in the RDS.

Magnet Style	Contingency
A (84)	30%
B (84)	25%
C (84)	35%

These contingencies were applied to the total cost of each magnet system. The differences in contingency rate were based on the relative complexity of the systems and the knowledge of the design features at the time of the RDS.

Since the RDS, considerably more details of the designs have been developed and, in particular, a number of dipole models have been constructed and tested for each design. These model tests have served to verify design features and, in some cases, confirm performance projections.

A large part of the magnet costs is due to the superconducting cable. Experience in cable procurement in the U.S. over the past year, as well as, the cable costs for the HERA project in Hamburg have served to confirm the unit costs projected in the RDS.

In view of the above information a more detailed contingency analysis is provided in this report. The contingency has been estimated for each WBS level 7 element of the dipole magnets. The details are shown in Tables D-1 through D-5 of Appendix D. For example, the contingency for materials costs is estimated at 10% for Superconductor and 15% for Yoke laminations and Helium and Vacuum containment systems. Most other material costs are estimated at 25%. The labor estimates in all level 7 components have a 35% contingency. These same contingency percentages are applied uniformly to each of the five magnet design styles of this report. Because of the different costs of components for each level 7 subsystem, this results in an average dipole contingency that varies from 18.1% for Design A to 20.6% for Design C.

The other components of the magnet systems have higher contingencies. While quadrupole designs should be relatively straight forward, no development models have been produced. A 25% contingency is applied to the quadrupoles. Spool pieces are extremely complex units and a higher contingency of 35% is applied.

Table III-19 provides a level 5 summary of the Magnet Systems Contingency. The top half of the Table shows the construction cost and contingency factor (%) for each of the magnet system components and for each of the 5 Design Styles. The lower half of the Table shows the resulting contingencies (K$) for each element, as well as, an overall average contingency factor for each design style.

2. Other Technical Systems

The conceptual details of the subsystems included under this category have not changed substantially since the RDS. The same contingency factor percentages that were developed for the RDS are applied here. The results are summarized in Table III-20 for each subsystem in each of the five design styles. The construction cost and the contingency factor (%) are shown in the top half of the Table. The resulting contingency (in K$) is provided in the lower half of the Table. The last line shows the average contingency for all subsystems.

3. Conventional Systems

In the RDS the contingency increased slightly with the collider ring circumference. This was done in part to provide a partial allowance for construction uncertainties associated with the access and installation concerns for using the long type C magnets. For example, the requirements for constructing and assembling the very long magnets is tied to tunnel access points and additional technical and assembly work space may be needed.

Another reason for the larger contingency used in conjunction with the larger circumference ring concerns an allowance to be made for design variations arising from the larger site. As the ring circumference increases, it is likely that additional support services facilities may need to be distributed around the collider ring.

Table III-19
Magnet Systems Contingency
(FY84 K$)

(WBS) 4.2.1.	STYLE: CONTINGENCY: A	PCT	B	PCT	D	PCT	C	PCT	C*	PCT
1 TOOLING	41,497	30	23,738	30	41,497	30	21,810	30	21,810	30
2 DIPOLE MAGNETS	573,837	18.1	642,937	20.3	646,421	18.6	278,358	20.6	381,744	20.5
3 QUADRUPOLE MAGNETS	38,341	25	54,346	25	42,397	25	19,048	25	24,762	25
4 SPEC. DEVICES/SPOOLS	37,543	35	75,818	35	67,874	35	84,667	35	110,067	35
5 SPEC. MAGNETS/INSERTIONS	14,286	30	14,286	30	14,286	30	14,286	30	14,286	30
6 INSTALLATION & SURVEY	26,750	30	58,765	30	40,833	30	23,306	30	34,286	30
TOTAL ADJUSTED MAG SYS	732,254		869,890		853,309		441,473		586,953	

14.2.1. CONTINGENCY COSTS	A	B	D	C	C*
1 TOOLING	12449.2	7121.4	12449.2	6542.9	6542.9
2 DIPOLE MAGNETS	103864.4	130516.3	120234.4	57341.8	78257.2
3 QUADRUPOLE MAGNETS	9585.3	13586.4	10599.3	4761.9	6190.5
4 SPEC. DEVICES/SPOOLS	13140.0	26536.5	23755.9	29633.3	38523.3
5 SPEC. MAGNETS/INSERTIONS	4285.7	4285.7	4285.7	4285.7	4285.7
6 INSTALLATION & SURVEY	8025.0	17629.5	12249.9	6991.7	10285.7
TOTAL CONTINGENCY COST:	151349.6	199675.8	183574.5	109557.3	144085.3
OVERALL CONTING PERCENTAGE:	20.7	23.0	21.5	24.8	24.6

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Table III-20

"Other" Technical Systems Contingency

(FY84 M$)

(WBS)	STYLE: CONTING: GENCY:	A	PCT	B	PCT	B	PCT	C	PCT	C*	PCT
1.4.2.	CONSTRUCTION COSTS:										
2	CRYOGENICS	129.0	20	121.0	20	136.0	20	137.0	20	150.0	20
3	VACUUM SYSTEMS	12.3	25	16.9	25	16.9	25	18.4	25	26.2	25
4	MAIN POWER SUPPLIES	21.0	20	21.0	20	21.0	20	21.0	20	21.0	20
5	CORRECTION POWER SUPPLIES	11.2	20	11.2	20	11.2	20	15.8	20	15.8	20
6	RF SYSTEM	7.7	20	9.3	20	7.7	20	30.9	20	30.9	20
7	INJECTION SYSTEM	2.9	30	2.9	30	2.9	30	2.9	30	2.9	30
8	ABORT SYSTEM	8.1	30	8.1	30	8.1	30	10.4	30	10.4	30
9	INSTRUMENTATION	7.0	30	7.0	30	7.0	30	10.3	30	10.3	30
10	CONTROLS	19.4	30	19.5	30	19.4	30	23.9	30	23.9	30
11	SAFETY SYSTEMS	5.4	30	5.9	30	5.4	30	10.1	30	10.1	30
	TOTAL "OTHER" TECH SYSTEMS COSTS:	224.1		222.9		235.7		280.6		301.4	
1.4.2.	CONTINGENCY COSTS:										
2	CRYOGENICS	25.8		24.2		27.2		27.4		30.0	
3	VACUUM SYSTEMS	3.1		4.2		4.2		4.6		6.5	
4	MAIN POWER SUPPLIES	4.2		4.2		4.2		4.2		4.2	
5	CORRECTION POWER SUPPLIES	2.2		2.2		2.2		3.2		3.2	
6	RF SYSTEM	1.5		1.9		1.5		6.2		6.2	
7	INJECTION SYSTEM	.9		.9		.9		.9		.9	
8	ABORT SYSTEM	2.4		2.4		2.4		3.1		3.1	
9	INSTRUMENTATION	2.1		2.1		2.1		3.1		3.1	
10	CONTROLS	5.8		5.8		5.8		7.2		7.2	
11	SAFETY SYSTEMS	1.6		1.8		1.6		3.0		3.0	
	TOTAL "OTHER" TECH SYS	49.7		49.8		52.3		62.8		67.4	
	OVERALL CONTING PERCENTAGE:	22.2		22.3		22.2		22.4		22.3	

It will, in general, be more difficult to find a site for the larger ring. Overcoming some of the site limitations could require that the collider tunnels be constructed deeper in the ground. Such a result would very quickly increase the cost of constructing the experimental halls and access shafts.

As a result of the above RDS analysis the contingency allowance (25%) was constant for all elements of the conventional systems except the main ring. For the main ring a variance in the contingency rates was recommended by PB because of the increased probability of unanticipated problems in the larger sized ring.

Approximately the same procedure is followed in this report as in the RDS. The contingency allowances for the main ring structures are 25% for Designs A and D, 25.5% for Design B, and 30% for Designs C and C*. A constant allowance of 20% is used for certain cryogenic facilities and support building structures. The results for each of the current Design Styles are indicated in Table III-21.

4. Systems Engineering

An average design contingency of 25% is applied to the EDI for Technical Systems. The rate was developed in the RDS from a detailed analysis of the various components. For conventional systems the contingency on the EDIA (AE/CM) varies from 25% for Designs A and D to 30% for Designs C and C* in view of the probability of additional design problems that may occur for the larger rings. The results are summarized in Table IV-1 of the next section.

Table III-21
Conventional Construction Contingency
(FY84 K$)

	STYLE:	A		B		B		C		C*	
	CONTINGENCY PERCENT:		PCT		PCT		PCT		PCT		PCT
	PARAMETER VALUES:										
	FIELD LEVEL, T	6.40		5.75		6.40		3.00		3.00	
	CIRCUMFERENCE, MI	57.17		62.14		57.17		106.88		106.88	
	(CIRCUMFERENCE, KM)	92.00		100.00		92.00		172.00		172.00	
(WBS) 1.4.1	CONVENTIONAL FACIL. SYSTEMS, COSTS:										
.1	LAND IMPROVEMENTS	15,300	25	16,631	25.5	15,300	25	28,005	30	28,005	30
.2.1	TUNNEL TYPE I	88,036	25	95,693	25.5	88,036	25	164,592	30	164,592	30
.2.2	TUNNEL TYPE II	90,249	25	98,097	25.5	90,249	25	168,725	30	168,726	30
.2.3	TUNNEL TYPE III	154,292	25	167,700	25.5	154,292	25	288,459	30	288,459	30
.2.4	TUNNEL (OTHER ELEMENTS) (CRYO, BM DUMP, RF, ETC)	13,927	20	13,927	20	13,927	20	13,927	20	13,927	20
.3	CRYOGENIC FACILITIES	7,998	20	7,998	20	7,998	20	7,998	20	7,998	20
.4	SUPPORT BUILDINGS	1,750	20	1,902	20	1,750	20	3,272	20	3,272	20
.5	UTILITIES	38,822	25	42,198	25.5	38,822	25	72,581	30	72,581	30
.6	ACCESS SHAFTS	0	25	0	25.5	0	25	13,540	30	13,540	30
	TOTAL CONVEN. FACILITIES	410,376		444,154		410,376		761,700		761,700	
	CONTINGENCY COSTS:										
.1	LAND IMPROVEMENTS	3,825		4,241		3,825		8,501		8,501	
.2.1	TUNNEL TYPE I	22,009		24,402		22,009		49,378		49,378	
.2.2	TUNNEL TYPE II	22,562		25,015		22,562		50,618		50,618	
.2.3	TUNNEL TYPE III	38,573		42,766		38,573		86,538		86,538	
.2.4	TUNNEL (OTHER ELEMENTS) (CRYO, BM DUMP, RF, ETC)	2,785		2,785		2,785		2,785		2,785	
.3	CRYOGENIC FACILITIES	1,600		1,600		1,600		1,600		1,600	
.4	SUPPORT BUILDINGS	350		380		350		654		654	
.5	UTILITIES	9,706		10,761		9,706		21,774		21,774	
.6	ACCESS SHAFTS	0		0		0		4,062		4,062	
	TOTAL CONSTR. CONTING. COSTS	101,410		111,949		101,410		225,990		225,990	
	OVERALL CONTINGENCY PERCENTAGE:	24.7		25.2		24.7		29.7		29.7	

IV. COST ROLLUP OF SSC MAGNET DEPENDENT SYSTEMS

The following table, Table IV-1, presents the complete tabulation of all of the Magnet Dependent System costs for the five magnet designs. The individual elements have all been presented in earlier sections of this report; they are combined here for the final summation. Again it should be re-emphasized, this "Total Cost" is for the SSC "magnet dependent systems" only, and should not be misinterpreted as a "Total SSC Construction Cost" for the entire project. In order to develop the "Total SSC Construction Cost" the costs for project management, injection accelerators, and other "common" technical and conventional systems must be included as shown in the 1984 RDS Report.

In the summation of Table IV-1, the Magnet Systems costs are those "CDG adjusted" values that were described in Section III-A-4. The Other Technical Systems costs were discussed in Section III-B, and the Conventional Systems costs are from Section III-C. The EDI and contingency costs were discussed in Sections III-D and III-E. Comparisons between the costs in Table IV-1 and the Reference Designs Study cost estimate are shown in Appendix E.

Table IV-1
Summary Cost Estimate
Magnet Dependent Systems
(FY84 K$)

SUMMARY COST ROLLUP
MAGNET DEPENDENT SYSTEMS ONLY

	STYLE A	STYLE B	STYLE D	STYLE C	STYLE C*
CONSTRUCTION COSTS:					
ADJUSTED MAGNET SYSTEMS	732.25	869.89	853.31	441.47	589.95
OTHER TECHNICAL SYSTEMS	224.10	222.90	235.70	200.60	301.40
CONVENTIONAL SYSTEMS	410.38	444.15	410.38	761.70	761.70
SUBTOTAL: CONSTRUCTION	1,366.73	1,536.94	1,499.38	1,403.77	1,653.05
SYSTEMS ENGINEERING COSTS:					
MAGNET SYSTEMS	83.87	103.78	100.42	58.18	76.66
OTHER TECHNICAL SYSTEMS	42.50	43.00	44.70	55.80	59.70
CONVENTIONAL SYSTEMS	65.66	71.06	65.66	121.87	121.87
SUBTOTAL: SYS. ENGIN.	192.03	217.84	210.78	235.85	258.24
CONTINGENCY COSTS:					
MAGNET SYSTEMS	151.35	199.68	183.57	109.56	145.09
OTHER TECHNICAL SYSTEMS	49.70	49.80	52.30	62.80	67.40
CONVENTIONAL SYSTEMS	101.41	111.95	101.41	225.99	225.99
SYSTEMS ENGINEERING	48.01	54.82	52.69	65.05	70.65
SUBTOTAL: CONTINGENCY	350.47	416.24	389.98	463.40	509.13
TOTAL MAGNET SYS. DEPEND. COSTS	1,909.23	2,171.03	2,100.14	2,103.02	2,420.42

APPENDIX A
COST ESTIMATING PARTICIPANTS AND DIPOLE MAGNET TASK FORCE MEMBERS

As stated earlier, many individuals and groups participated in the development of the particular cost estimating data presented in this report. The report was prepared with three major cost sections for the Magnet Dependent Costs (Magnet Systems, Other Technical Systems, and Conventional Systems). The major styles being considered and the lead groups responsible for initially developing and providing the primary cost detail materials are indicated below:

MAGNET SYSTEMS:
  Cosine Theta Style Dipole Magnets:
    Magnet Style A - Tooling and Dipole Magnets, BNL
    Magnet Style B - Tooling and Dipole Magnets, FNAL
    Magnet Style D - Tooling and Dipole Magnets, BNL & FNAL, GD, W
      (General Dynamics, Westinghouse)
  Superferric Style Magnets:
    Magnet Style C - Tooling and Dipole Magnets, TAC, GD, W
    Magnet Style C*- Tooling and Dipole Magnets, TAC

OTHER TECHNICAL SYSTEMS:
  Cryogenics A, D - BNL; B - FNAL; C - TAC, CCI
  All other systems - CDG

CONVENTIONAL FACILITIES:
  Conventional Facilities - PB, RTK, CDG
    (Parsons Brinckerhoff, Raymond Kaiser, Tudor, Keller &
    Gannon-Knight)

In addition to the laboratory, university groups, and industrial participants, the SSC Central Design Group reviewed, analyzed, and prepared cost estimates as well. The CDG groups also prepared the estimates for EDI and Contingency. The primary CDG personnel responsible for each of the above categories are listed below:

Magnet Systems: T. Elioff, R. Yourd, K. Mirk, P. Limon
Other Technical Systems: T. Elioff, P. Limon
Conventional Systems: J. Sanford, T. Toohig

For a detailed review of the dipole magnet costs, a Dipole Magnet Cost Estimating Task Force was assembled and met with the CDG during July, 1985. Various cost consultants also participated in these meetings. A list of the Task Force Members and Consultants, and a schedule of the meetings at the CDG is shown in Table A-1.

Table A-1
SSC-CDG DIPOLE MAGNET COST ESTIMATING TASK FORCE
JULY 18-24, 1985

Participants:

Task Force:	Tom Elioff, Ron Yourd, Ken Mirk, Carl Goodzeit
Laboratory Consultants:	Norb Engler, Greg Kobliska, Russ Huson,
Industrial Estimates:	General Dynamics (Bob Baldi), Westinghouse (Andy Jarabak)

Agenda:

July 18, 1985

9 - 10am	Introduction: describe scope of our work, the procedures we will use to assemble report, the materials available, and how we will arrive at a CDG table of costs for overall comparisons.
10am - 4pm	Review Design Style D: laboratory estimates, GD materials, and Westinghouse materials; review material quotes and unit costs;

July 19, 1985

9 - 12am	Review Design Style A: laboratory estimates, BNL scaling factors, extrapolation of style D data base, etc.
1 - 4pm	Review Design Style B: laboratory estimate, FNAL data extrapolation from style D data base, etc.

July 22, 1985

9am - 4pm	Complete Style D Package: review Carl's aperture scaling factors, length factors, Quadrupoles, Spool Pieces, Installation, Cryogenic Systems, etc.

July 23, 1985

9am - 4pm	Review Style C and C* Materials: review laboratory estimates, review GD and Westinghouse estimates, assemble CDG estimate, evaluate scaling factors, etc.

July 24, 1985

1 - 4pm	Review Complete Style C and C* Packages

APPENDIX B
MAGNET COST DATA COMPARISONS

The following tables (Tables B-1, B-2, and B-3) present the individual cost comparisons from the cost estimating participants for the Style A, B, and D design respectively. They show the laboratory and CDG detail comparisons and for Design D shows the industrial estimates from General Dynamics and Westinghouse for comparison.

Tables (Tables B-4 and B-5) present the individual cost comparisons from the cost estimating participants for the Style C, and C* designs respectively. They also show the laboratory and CDG detail comparisons and for Design C shows the Industrial estimates from General Dynamics and Westinghouse.

The CDG projection is the estimate that is carried forward throughout the cost comparison report. It is apparent from the comparisons that some of the estimators did not address all of the detail elements in the same manner (for example, often the shop support functions, testing, and allowance factor areas were incomplete). The CDG estimate is presented as the most complete and thoroughly integrated package, appropriate for the cost comparison study.

1. General Discussion of the Estimating Methods

In comparing the estimates in Tables B-1 through B-3, and in particular to explain how certain CDG assessments were developed, the following discussion will describe particular features of the laboratory and industrial estimates in detail. The general comments will focus on the estimates for style D since most of the new detail analysis was done on that system and because that is the cosine theta style that the industrial participants reviewed. Table B-3.1 presents the "per magnet" cost for materials and labor hours for the laboratory, the CDG, GD, and Westinghouse.

An overall assessment at the bottom line showing total labor of 561, 585, 616, and 703 hours respectively for the Labs, CDG, GD, and W indicate surprisingly good agreement and a common understanding of the overall direct labor effort necessary for the Style D dipole magnet assembly. Common labor rates, $/hr, were developed and prescribed by the CDG to describe a national average; a range of labor classifications was indicated to allow for differing skill level requirements. The common CDG labor rates were not used by the industrial estimators. Although the GD estimate does not reveal the specific labor rate they use for each of the labor groups represented in the estimate (because of their proprietary individual labor rate structure), their total "labor-to-dollar" conversion for all of their project labor would indicate an overall net rate of approximately $45/hr (probably representative of the overall GD-Convair San Diego facilities). While this is not the particular rate for each specific shop or factory labor task in their estimate, this net rate serves to indicate that the GD labor base is substantially higher than the CDG analysis for a national average labor rate ranging from $21-$42/hr for technician and shop skill levels. The Westinghouse estimate assumes a relatively high skill level (if it is correlated to the CDG rates), and their net effective labor rate indicates an overall labor average of $35/hr. The laboratory estimates use the specific CDG rates as prescribed, and generally indicate that even the "lower skill level" technician rates would be adequate for most of their labor tasks. The CDG estimate reflects the overall rates also, but we assume a mix of skill levels for all labor that reflects an overall rate blend of $23/hr for direct labor; $32/hr for supervision and support. The resulting effect of these labor rate differences for each of the estimators results in higher labor costs indicated by the GD and Westinghouse estimates than for the laboratory and CDG estimates, even though the total labor "hours" are nearly identical.

An overall assessment at the bottom line (Table B-3.1) showing a total cost for materials of $66,973, $71,723, $89,262, and $82,014 respectively for the Labs, CDG, GD, and W would indicate generally good agreement with the exception of the high GD value. The GD value includes an overall general allowance of $11,210 that accounts for a large portion of the difference; this overall allowance factor is GD's method for handling miscellaneous allowances for "low dollar allocations," "material usage variance," "damaged materials," etc. This value appears to be extraordinarily large in our analysis since we find that most of the parts were itemized materials from drawings and parts lists and were costed explicitly from the low level WBS categories. We feel that the CDG suggested allowance factor of 5% for the overall superconductor purchase quantity and 1% excess for all other materials is adequate for a materials variance, and that higher values for breakage and damage, design "growth" and vendor "Class II" changes should be treated as a contingency and not a direct cost.

GD has added a factor for fee and cost of money which we have not included in the CDG estimates, its inclusion being inconsistent with the management and risk assumption model used for this estimate. Inclusion of these items in a self-consistent way requires knowledge of the particular contracting vehicle being used and to be useful would have to be obtained through competitive bidding procedures.

In noting certain of the other "row-by row" comparisons for the WBS elements in the tables for Design D, we should comment that the CDG estimate largely reflects the cost estimate detail from the laboratory estimate columns, and that the industrial estimates were used primarily for overall consistency checks, particular vendor quotation sources, task and labor estimate confirmation, etc.

2. Cosine Theta Styles

Design D: All of the cost estimates for the cold bore tube rely on the BNL estimate for the copper coated bore tube with a Multiwire correction coil package applied. The CDG provided this base cost information to both GD and Westinghouse for their use, since we felt that in this case considerable R&D had been done by BNL, that the actual design was specific to a "Multiwire" process, and that it would not be as efficient for them to individually deal with the same "Multiwire" personnel. However, GD did adjust the material and labor costs slightly to add additional cleaning, testing, and inspection steps.

The coil costs are largely dominated by the superconductor material unit cost; this unit cost was also developed by the CDG and supplied to all the estimators as a common cost base for all to use. The coil collaring costs depend on certain specification requirements; the GD and Westinghouse estimates are based on a cost for "Nitronic-40" material, a specific Armco product. This specific material was prescribed by BNL in the basic collar designs and has subsequently been adjusted to a "more generic" stainless steel of a type 304-N or equivalent. The material cost differences account for most of the differences between the estimate details. The CDG costs assume the lower cost stainless alloy will be incorporated into the design.

For the "yoke and components," again most of the cost difference in materials depends on particular "anticipated assumptions" in the lamination material requirements or stamping tolerance requirements. The CDG estimate selected for the cost comparison a nominal material cost of 0.34 $/lb and a stamping cost ranging from 0.05 to 0.08 $/each depending on the size and tolerance requirement. It was felt that these were representative current costs based on the large experience base for other similar magnet lamination costs and did not necessarily reflect any one particular vendor quote or cost source. The range of vendor quotations in the various estimates was surprisingly wide considering our expectation that the "lamination cost" would be one of the most well-established and consistent cost packages. In fact, the vendors hesitated to bid on such very large and future projections since the "anticipated requirements" for stamping acceptance (burr requirement, precision and uniformity, relative tolerances between corresponding lamination sections) and the particular material requirements that are "anticipated" (test and certification data, permeability range selection, surface conditions, packaging, etc.) were not clearly delineated in these R&D design packages.

It is apparent in reviewing all of the estimates that the "R&D model" drawing packages that were developed by the laboratories (and were sent to the estimators) and that were subsequently sent out for vendor quotations were obviously not representative of what will be eventually developed into "magnet production" drawings. Since the drawings have not received a "manufacturing analysis" and/or a "value engineering review," the vendors were asked to present estimates that often required certain ranges of assumptions; therefore, the particular estimates were not always comparable and required some interpretation.

The comparison of the remaining "material" elements for design D, however, appear to be fairly consistent with the exception of the Westinghouse estimate for the vacuum vessel components. Their value is several thousand dollars higher than the others with no apparent explanation, other than perhaps individual vendor "quotation" interpretations as described above.

The labor estimates for direct and indirect shop support are developed by each group in a different manner. The CDG estimate assumes an overall percentage of 23% of the "direct labor" is required for additional shop support. The industrial estimates reflect other equivalent percentages, and some inconsistencies occur here in trying to define adequately which shop services are covered by the labor "overhead factors" on the direct labor rates, and which supporting services are covered directly by Project Management or EDI (including QA) categories.

In examining the overall estimates for the full magnet system production, it should be remembered that for the CDG estimate, in addition to the entries shown for the "Total Cost for Tooling and Dipole Magnets" the complete cost includes additional costs developed and collected within the overall "SSC Project Management" and "Systems Engineering and Design" (EDI) WBS elements.

Design A: The CDG cost estimate summation for Design A utilizes the base information for the Design D estimate, and the yoke and cryostat costs are scaled for a size adjustment.

Design B: The CDG estimate for Design B utilizes the laboratory (FNAL) base information with the following exceptions. For the material estimate, we adjust the interconnection material to be consistent with the Design D interconnection base, and add a cost for a single internal bypass bus to the electrical package. In addition we add the same factors for Material Allowances and Reject Allowances as in the other designs. Other material cost factors result from specific design differences described for style B. One notable overall difference is in the cold bore tube; FNAL design B proposes an aluminum bore tube with "transition metal ends" to be connected to stainless steel bellows in the interconnection regions. The bore tube is proposed to have separate correction coil windings incorporated as opposed to the "Multiwire" concept described for Designs D and A. The estimated cost of such a system was developed by FNAL and also was used directly in the CDG estimate. The bore tube estimate used here appears to be considerably less expensive than the estimates for Designs D and A and we have not made a detail analysis of the differences for this study; a similar design concept should conceivably work for all cosine theta type systems, and similar costs should be reflected in all the estimates. Another difference between the designs is in the coil collars; Design B proposes aluminum collars, Design D (and A) uses stainless steel. Again, we have used the costs as proposed by FNAL for their system, but point out this difference in design concept.

For the labor estimate, the CDG estimate follows the same format as in the other systems whereby we describe an allowance for additional overall shop support (factor of 23%) based on the direct labor. We also assume a difference in the coil fabrication concept for this study: the CDG estimate is based on the "wet winding" coil fabrication concept that is consistent with that described for Designs D and A, (and in fact the actual Design D labor cost base was used after proper length scaling for Design B); the FNAL estimate is based on a "dry winding" method that is under development and consideration. Once again, if the dry winding method is successful and is adopted for the cosine theta style production, its cost savings should be reflected in all of the cosine theta designs accordingly.

3. Superferric Styles.

The cost estimates for Designs C and C* are shown in Tables B-4 and B-5. There is considerably more disparity between the estimates presented by the Laboratory group (TAC), CDG, GD and Westinghouse in the case of Design C than was evident in Design D (Table B-3 above). As evident in examining the first section of Table B-3.1, the laboratory estimate does not address the particular sections for internal bus work, magnet interconnections, and the various testing and measurement operations, as well as the allowances for material factors and rejects. The CDG estimate treats all of these elements in a comparable manner as was described for the cosine theta styles; i.e. we assume the same model holds for rejects, material factors, cold and warm magnetic measurements, and for shop support.

Design C: The apparent large discrepancy in treating the interconnection region parts hardware (materials) (CDG: $200, GD: $10630, and W: $2350.) occurs due to the different way of describing the expansion joints. The CDG estimate counts only the few dipole to dipole interconnection components with the dipole magnet costs; the CDG counts the dipole to spool piece connection as part of the "Special Devices/Spools" costs. The actual dipole-to-dipole hardware for design C is very small (essentially a "hard" magnet to magnet connection with no expansion joint) compared to the corresponding area for designs 0, A, and B (where all of the bellows, buss connections, and cryogenic contractions are allowed). All of the equivalent bellows, bus flex joints, and contraction regions for design C were costed by the industrial firms, but were "pro-rated" to show a somewhat equivalent "per-dipole" allowance and were collected with the dipole cost as being equivalent to the interconnection area for Design 0. This discrepancy distorts the dipole costs, and the CDG estimate more appropriately costs the large interconnection Design C box with the "Special Devices" category in the overall "Magnet Systems" table.

Another large discrepancy occurs in the "Internal Bus Work" category. The laboratory package does not include an estimate for this area, and the design was very ill-defined at the time that the industrial groups were asked to estimate. Subsequently, a design for the bus links and connections has been defined by TAC, and a careful attempt to cost the components on a basis comparable to the estimates developed for the cosine theta styles leads to the total cost reflected by the CDG. This package appears to be a high cost item, but it should be remembered that there are many high current connection legs for each bore (e.g., two separate dipole windings at 12,000 A, 1 dipole winding at 3000A, quadrupoles, correctors, etc.) and long magnet lengths that need to be properly counted.

The labor hours for the Design C estimate were examined in considerable detail by the CDG and the values shown represent a composite CDG assessment after separate review of each task and work package. They appear to be somewhat intermediate between the laboratory and industrial estimates overall; they appear to be nearly the same as the laboratory estimates for coil and yoke fabrication, but they are considerably higher than the laboratory estimates in the areas of cryostat and vacuum vessel assembly. In addition, separate labor estimates are shown for the testing, measurement and support tasks, as well as the shop support categories.

Design C*: Design C* was developed by direct extrapolation and scaling of the Design C costs. No additional review or comparison checks were made.

"A" BNL-CDG comparisons 4

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Table B—1.1

Design A Magnet Comparisons

Cost Per Each Dipole Magnet

PER EACH DIPOLE MAGNET - STYLE A

(WBS)	ITEM	LABORATORY ESTIMATE (BNL & FNAL) MATL $	LBR HRS	LABOR $	TOTAL $	CENTRAL DESIGN GROUP ESTIMATE MATL $	LBR HRS	LABOR $	TOTAL $
8	MAGNETS - DIRECT MATLS AND LABOR,							23.0	
14212. 1.1	COLD BORE TUBE	5273.0	60.5	1494.6	6767.6	5273.0	60.5	1575.5	6848.5
1.2	COILS	63333.3	292.9	7292.5	70625.8	65750.0	292.9	6736.7	72486.7
1.3	COIL COLLARING	12282.0	69.6	1465.0	13748.6	12202.0	69.6	1600.0	13803.6
2.1	YOKE AND COMPONENTS	15416.8	43.6	1240.3	16657.1	15070.0	43.6	1002.0	16072.0
2.2	HELIUM CONTAINMENT VESSEL	5444.6	16.6	401.2	5845.8	5444.6	16.6	381.8	5826.4
3.1	COLD MASS SUBASSEMBLY PREP	832.2	15.3	358.7	1190.9	832.2	15.3	351.9	1184.1
3.2	20K HEAT SHIELD	912.9	18.9	440.9	1353.8	912.9	18.9	434.7	1347.6
3.3	80K HEAT SHIELD	2558.4	18.7	436.7	2995.1	2558.4	18.7	430.1	2988.5
3.4	UPPER VACUUM VESSEL	3562.8	14.5	412.3	3975.1	3562.8	14.5	333.5	3896.3
3.5	LOWER VACUUM VESSEL	1744.6	19.6	508.4	2253.0	1744.6	19.6	450.8	2195.4
3.6	VESSEL ENDS	475.5	13.0	416.0	891.5	475.5	13.0	299.0	774.5
4.1	INTERNAL BUS WORK	3553.7	103.0	2163.0	5716.7	3553.7	103.0	2369.0	5922.7
5.1	INTERCONNECTION REGION PARTS	2569.0	22.0	704.0	3273.0	5000.0	22.0	506.0	5506.0
5.2	SHIPPING/STORAGE/HANDLING				0.0	30.0			30.0
6.1	TESTING				0.0		8.0	184.0	184.0
6.2	WARM MAGNETIC MEASUREMENTS	-	3.5	80.0	80.0		16.0	368.0	368.0
6.3	COLD MAGNETIC MEASUREMENTS	150.0	5.0	160.0	310.0	150.0	8.0	184.0	334.0
6.4	CRYOGENIC TESTING FACILITY OPERNS.				0.0		4.0	92.0	92.0
8.1	DIRECT SHOP SUPPORT				0.0				0.0
8.2	MISCEL. AND INDIRECT SHOP SUPPORT		180.0	5760.0	5760.0	200.0	180.0	5760.0	5960.0
	MATERIAL FACTORS & ALLOWANCES	3634.0			3634.0	4000.0			4000.0
	ALLOWANCE FOR REJECTS	2000.0	14.0	294.0	2294.0	2000.0	14.0	322.0	2322.0
	SUBTOTAL	123743.6	917.7	23628.4	147372.0	129640.5	946.2	23382.6	153023.1

Table B—1.2

Design A Magnet Comparisons

Total Dipole Magnet Costs for Tooling and Full Production

"A" BNL-CDG comparisons 4

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PER 4200 DIPOLE MAGNETS - STYLE A ITEM (WBS)			LABORATORY ESTIMATE: (BNL + FNAL)				CENTRAL DESIGN GROUP ESTIMATE			
			MATL K$	LBR KHRS	LABOR K$	TOTAL K$	MATL K$	LBR KHRS	LABOR K$	TOTAL K$
A	TOOLING - DIRECT									
14211. 1.1	COIL PRODUCTION		17,269	299	10,340	27,609	17,269	299	10,340	27,609
1.2	YOKES, COLLARS, HE CONTN.		6,957	15	571	7,528	6,957	15	571	7,528
1.3	ELECTRICAL SYSTEMS		198	2	71	269	198	2	71	269
1.4	FINAL ASSEMBLY - CRYOSTAT		10,239		0	10,239	10,239		0	10,239
1.5	TESTING AND MEASUREMENTS		341	14	491	832	341	14	491	832
	SUBTOTAL (MAGNET 'TOOLING' DIRECT)	4.2	35,004	320	11,472	46,476	35,004	330	11,473[1]	46,477
B	MAGNETS - DIRECT MATLS AND LABOR,									
14212. 1.1	COLD BORE TUBE		22,147	208	6,277	28,424	22,147	208	6,617	28,764
1.2	COILS		266,000	1,230	30,638	296,638	276,150	1,230	28,294	304,444
1.3	COIL COLLARING		51,588	292	6,156	57,744	51,588	292	6,723	58,311
2.1	YOKE AND COMPONENTS		64,751	183	5,209	69,960	66,854	183	4,212	70,066
2.2	HELIUM CONTAINMENT VESSEL		22,867	70	1,685	24,552	22,867	70	1,604	24,471
3.1	COLD MASS SUBASSEMBLY PREP		3,495	64	1,507	5,002	3,495	64	1,418	4,913
3.2	20K HEAT SHIELD		3,834	79	1,852	5,686	3,834	79	1,806	5,640
3.3	80K HEAT SHIELD		10,745	79	1,834	12,579	10,745	79	1,807	12,552
3.4	UPPER VACUUM VESSEL		14,963	61	1,732	16,695	14,963	61	1,401	16,364
3.5	LOWER VACUUM VESSEL		7,328	82	2,135	9,463	7,328	82	1,893	9,221
3.6	VESSEL ENDS		1,997	55	1,747	3,744	1,997	55	1,256	3,253
4.1	INTERNAL BUS WORK		14,925	433	9,085	24,010	14,925	433	9,950	24,875
5.1	INTERCONNECTION REGION PARTS		10,790	92	2,957	13,747	21,000	92	2,195	23,195
5.2	SHIPPING/STORAGE/HANDLING		0	0	0	0	126	0	0	126
6.1	TESTING		0	0	0	0	0	34	773	773
6.2	WARM MAGNETIC MEASUREMENTS		0	10	336	336	0	67	1,546	1,546
6.3	COLD MAGNETIC MEASUREMENTS		630	21	672	1,302	630	34	773	1,403
6.4	CRYOGENIC TESTING FACILITY OPERNS.		0	0	0	0	0	17	386	386
8.1	DIRECT SHOP SUPPORT		0	0	0	0	0	0	0	0
8.2	MISCEL. AND INDIRECT SHOP SUPPORT		0	756	24,192	24,192	840	756	24,192	25,032
	MATERIAL FACTORS & ALLOWANCES		15,263	0	0	15,263	16,000	0	0	16,000
	ALLOWANCE FOR REJECTS		8,400	59	1,235	9,635	8,400	59	1,352	9,752
	SUBTOTAL		519,723	3,854	99,239	618,962	544,400	3,914	98,287	642,687
	TOTAL COST FOR TOOLING + DIPOLE MAGNETS		554,727	4,174	110,712	665,439	579,404	4,234	109,760	689,164

"B" FNAL-CDG comparisons 4

8/07/85

Table B–2.1

Design B Magnet Comparisons

Cost Per Each Dipole Magnet

PER EACH DIPOLE MAGNET - STYLE B
ITEM

(WBS)		LABORATORY ESTIMATE (FNAL)				CENTRAL DESIGN GROUP ESTIMATE			
		MATL $	LBR HRS	LABOR $	TOTAL $	MATL $	LBR HRS	LABOR $	TOTAL $
B	MAGNETS - DIRECT MATLS AND LABOR,							23.0	
14212. 1.1	COLD BORE TUBE	410.0	30.0	790.0	1200.0	410.0	30.0	690.0	1100.0
1.2	COILS	23488.0	36.0	767.0	24255.0	23488.0	120.0	2760.0	26248.0
1.3	COIL COLLARING	3941.0	162.0	3578.0	7519.0	3941.0	30.0	690.0	4631.0
2.1	YOKE AND COMPONENTS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.2	HELIUM CONTAINMENT VESSEL	2186.0	44.0	1148.0	3334.0	2186.0	44.0	1012.0	3198.0
3.1	VACUUM VESSEL	7534.0	0.0	0.0	7534.0	7534.0	0.0	0.0	7534.0
3.2	HEAT SHIELDS	2342.0	0.0	0.0	2342.0	2342.0	0.0	0.0	2342.0
3.3.1	SUPPORTS (PARTS AND SUBASSY)	1064.2	42.8	898.8	1963.0	1064.2	42.8	984.4	2048.7
3.3.2	SUPPORTS (INSTALL)	0.0	31.4	659.4	659.4	0.0	31.4	722.2	722.2
		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5.1	FINAL ASSEMBLY LABOR		61.2	1285.2	1285.2		61.2	1407.6	1407.6
4.1	INTERNAL BUS WORK	0.0	0.0	0.0	0.0	560.0	5.0	115.0	675.0
6.1	INTERCONNECTION REGION PARTS	1414.0	20.0	640.0	2054.0	2700.0	20.0	460.0	3160.0
6.2	SHIPPING/STORAGE/HANDLING				0.0	30.0			30.0
6.1	TESTING				0.0		8.0	184.0	184.0
6.2	WARM MAGNETIC MEASUREMENTS				0.0		8.0	184.0	184.0
6.3	COLD MAGNETIC MEASUREMENTS	784.0			784.0	150.0	4.0	92.0	242.0
6.4	CRYOGENIC TESTING FACILITY OPERNS.				0.0		4.0	92.0	92.0
8.1	DIRECT SHOP SUPPORT				0.0				0.0
8.2	MISCEL. AND INDIRECT SHOP SUPPORT				0.0		100.0	3200.0	3200.0
	MATERIAL FACTORS & ALLOWANCES				0.0	1300.0			1300.0
	ALLOWANCE FOR REJECTS	250.2	6.7	141.4	391.6	675.0	7.0	161.0	836.0
	SUBTOTAL	43413.5	434.1	9907.8	53321.3	46460.2	515.4	12754.2	59214.4

Table B−2.2

Design B Magnet Comparisons

Total Dipole Magnet Costs for Tooling and Full Production

"B" FINAL-CDG comparisons 4

8/02/85

PER 13392 DIPOLE MAGNETS - STYLE B ITEM (WBS)	FINAL COST ESTIMATE MATL K$	 LBR KHRS	 LABOR K$	 TOTAL K$	CENTRAL DESIGN GROUP ESTIMATE MATL K$	 LBR KHRS	 LABOR K$	 TOTAL K$
A TOOLING - DIRECT								
14211. 1.1 COIL PRODUCTION	13,111	12	250	13,361	13,111	12	250	13,361
1.2 YOKES, COLLARS, HE CONTN.	8,202	12	253	8,455	8,202	12	253	8,455
1.3 ELECTRICAL SYSTEMS	216			216	216			216
1.4 FINAL ASSEMBLY - CRYOSTAT (INCL ABOVE)				0				0
1.5 TESTING AND MEASUREMENTS	2,669	65	1,357	4,026	2,669	65	1,357	4,026
SUBTOTAL (MAGNET 'TOOLING' DIRECT) 13.30	24,198	89	1,860	26,058	24,198	89	1,860	26,058
B MAGNETS - DIRECT MATLS AND LABOR.								
14212. 1.1 COLD BORE TUBE	5,491	402	10,580	16,070	5,491	402	9,240	14,731
1.2 COILS	314,551	488	10,272	324,823	314,551	1,607	36,962	351,513
1.3 COIL COLLARING	52,770	2,170	47,917	100,684	52,770	402	9,240	62,010
2.1 YOKE AND COMPONENTS	0	0	0	0	0	0	0	0
2.2 HELIUM CONTAINMENT VESSEL	29,275	589	15,374	44,649	29,275	549	13,554	42,829
3.1 VACUUM VESSEL	100,895	0	0	100,895	100,895	0	0	100,895
3.2 HEAT SHIELDS	31,364	0	0	31,364	31,364	0	0	31,364
3.3.1 SUPPORTS (PARTS AND SUBASSY)	14,252	573	12,017	26,269	14,252	573	13,183	27,435
3.3.2 SUPPORTS (INSTALL)	0	421	8,831	8,831	0	421	9,072	9,072
5.1 FINAL ASSEMBLY LABOR	0	0	0	0	0	0	0	0
4.1 INTERNAL BUS WORK	0	820	17,211	17,211	0	820	18,851	18,851
6.1 INTERCONNECTION REGION PARTS	0	0	0	0	7,500	67	1,540	9,040
6.2 SHIPPING/STORAGE/HANDLING	18,936	268	8,571	27,507	36,150	268	6,160	42,310
6.1 TESTING	0	0	0	0	402	0	0	402
6.2 WARM MAGNETIC MEASUREMENTS	0	0	0	0	0	107	2,464	2,464
6.3 COLD MAGNETIC MEASUREMENTS	0	0	0	0	0	107	2,464	2,464
6.4 CRYOGENIC TESTING FACILITY OPERNS.	10,500	0	0	10,500	2,009	54	1,232	3,241
8.1 DIRECT SHOP SUPPORT	0	0	0	0	0	54	1,232	1,232
8.2 MISCEL. AND INDIRECT SHOP SUPPORT	0	0	0	0	0	0	0	0
MATERIAL FACTORS & ALLOWANCES	0	0	0	0	0	1,379	42,054	42,054
ALLOWANCE FOR REJECTS	0	0	0	0	18,401	0	0	18,401
	3,351	90	1,894	5,245	9,040	94	2,150	11,190
SUBTOTAL	581,394	5,814	132,686	714,080	622,196	6,002	170,804	793,000
TOTAL COST FOR TOOLING + DIPOLE MAGNETS	605,592	5,902	134,546	740,138	646,394	6,091	172,664	819,058

BNL-CDG-GD-W comparisons 4

[illegible]

Table B—3.1
Design D Magnet Comparisons
Cost Per Each Dipole Magnet

PER EACH DIPOLE MAGNET - STYLE D

(WBS)	ITEM	LABORATORY ESTIMATE (BNL & FNAL)				CENTRAL DESIGN GROUP ESTIMATE				GENERAL DYNAMICS ESTIMATE				WESTINGHOUSE ESTIMATE			
		MATL $	LBR HRS	LABOR $	TOTAL $	MATL $	LBR HRS	LABOR $	TOTAL $	MATL $	LBR HRS	LABOR $	TOTAL $	MATL $	LBR HRS	LABOR $	TOTAL $
	MAGNETS - DIRECT MATLS AND LABOR.							23.0									
1212. 1.1	COLD BORE TUBE	2636.5	34.3	747.3	3383.8	2636.0	34.2	788.9	3424.9	3137.0	41.0			2384.0	6.7	212.0	2596.0
1.2	COILS	31668.6	146.5	3646.3	35314.9	30875.0	146.5	3369.5	34244.5	31400.0	133.9			35650.4	46.5	1395.0	37045.4
1.3	COIL COLLARING	6141.4	34.0	732.9	6874.3	6141.0	34.0	800.4	6941.4	9021.0	55.9			6904.7	30.3	744.0	7648.7
2.1	YOKE AND COMPONENTS	8841.5	38.7	1083.2	9924.7	9341.0	38.7	890.1	10231.1	11256.0	40.1			12409.8	65.0	2062.0	14471.8
2.2	HELIUM CONTAINMENT VESSEL	3196.1	14.4	353.8	3549.9	3196.0	14.4	331.9	3527.9	3180.5	15.0			970.0	71.0	2063.0	3033.0
3.1	COLD MASS SUBASSEMBLY PREP	803.0	15.0	348.0	1151.0	803.0	15.0	345.0	1148.0	2959.7	72.0			768.2	25.1	1444.0	2212.2
3.2	20K HEAT SHIELD	912.9	18.9	440.9	1353.8	913.0	18.9	434.7	1347.7	2232.0	14.3			966.7	18.2	734.0	1700.7
3.3	80K HEAT SHIELD	2173.1	18.7	436.7	2609.8	2173.0	18.7	430.1	2603.1	1185.3	14.3			1867.0	29.6	1287.0	3154.0
3.4	UPPER VACUUM VESSEL	2882.9	16.5	412.3	3295.2	2883.0	14.5	333.5	3216.5	4435.0	44.3			11545.3	63.4	2621.0	14166.3
3.5	LOWER VACUUM VESSEL	1470.7	19.6	508.4	1979.1	1471.0	19.6	450.0	1921.0	1631.1	44.3			912.0	37.5	1577.0	2489.0
3.6	VESSEL ENDS	415.0	13.0	416.0	831.0	415.0	13.0	299.0	714.0	0.0				230.1	43.0	1772.0	2002.1
4.1	INTERNAL BUS WORK	3013.2	51.5	1281.5	4294.7	1176.9	51.5	1184.5	2361.4	684.7	18.6			1419.2	44.6	1827.0	3246.2
5.1	INTERCONNECTION REGION PARTS	2540.0	22.0	506.0	3046.0	3600.0	22.0	506.0	4106.0	5092.0				2754.4			2754.4
5.2	SHIPPING/STORAGE/HANDLING				0.0	30.0			30.0	32.1	2.9			95.0	5.0	160.0	255.0
6.1	TESTING				0.0		8.0	184.0	184.0	0.0	54.0						0.0
6.2	WARM MAGNETIC MEASUREMENTS		7.5	180.0	180.0		8.0	184.0	184.0	0.0					10.0	290.0	290.0
6.3	COLD MAGNETIC MEASUREMENTS	150.0	5.0	160.0	310.0	150.0	4.0	92.0	242.0	0.0					[illegible]	29.0	29.0
6.4	CRYOGENIC TESTING FACILITY OPRNS				0.0		4.0	92.0	92.0	0.0							0.0
8.1	DIRECT SHOP SUPPORT				0.0				0.0	0.0	30.0						4561.5
8.2	MISCEL. AND INDIRECT SHOP SUPPORT		925.7	3318.0	3318.0	200.0	110.0	3520.0	3720.0	666.9	25.6				175.1	5916.0	5916.0
	MATERIAL FACTORS & ALLOWANCES	1817.0			1817.0	5000.0			5000.0	11210.7				0.0			0.0
	ALLOWANCE FOR REJECTS	1112.0	8.3	222.0	1334.0	1120.0	10.0	230.0	1350.0	1055.7	7.5			1081.5	9.0	390.0	1471.5
	SUBTOTAL	69973.0	581.4	14691.3	84665.2	71723.0	585.0	14405.7	[illegible]	89262.4	616.0			83814.1	588.2	25408.0	107446.1

Table B–3.2

Design D Magnet Comparisons

Total Dipole Magnet Costs for Tooling and Full Production

F* BNL-CDG-GD-W comparisons 4

3/03/85

PER 8400 DIPOLE MAGNETS - STYLE D ITEM (WBS)	LABORATORY ESTIMATE (BNL & FNAL)				CENTRAL DESIGN GROUP ESTIMATE				GENERAL DYNAMICS ESTIMATE				WESTINGHOUSE ESTIMATE			
	MATL K$	LBR KHRS	LABOR K$	TOTAL K$	MATL K$	LBR KHRS	LABOR K$	TOTAL K$	MATL K$	LBR KHRS	LABOR K$	TOTAL K$	MATL K$	LBR KHRS	LABOR K$	TOTAL K$
TOOLING - DIRECT																
1211. 1.1 COIL PRODUCTION	17,293	899	10,342	27,680	17,268	799	10,340	27,609					9,575	19	589	0
1.2 YOKES, COLLARS, HE CONTR	6,957	15	571	7,528	6,957	15	571	7,528					17,170	64	1,843	19,219
1.3 ELECTRICAL SYSTEMS	189	7	71	260	189	7	71	260								0
1.4 FINAL ASSEMBLY - CRYOSTAT	10,730		0	10,730	10,730		0	10,730					4,315			4,315
1.5 TESTING AND MEASUREMENTS	341	14	491	832	341	14	491	832					730			730
SUBTOTAL (MAGNET 'TOOLING' DIRECT)	8.4 35,004	320	11,472	46,476	35,004	320	11,473	46,477	15,740	250			31,891	83	2,851	34,381
MAGNETS - DIRECT MATLS AND LABOR																
4012. 1.1 COLD BORE TUBE	22,147	280	6,277	28,424	22,142	280	6,581	28,756	36,352	344			28,400	57	1,400	29,800
1.2 COILS	265,999	1,331	30,030	296,029	276,150	1,331	28,304	304,454	300,400	1,135			290,463	389	10,718	301,181
1.3 COIL COLLARING	51,588	292	6,156	57,744	51,584	292	6,773	58,357	75,776	470			57,990	305	6,699	64,689
2.1 YOKE AND COMPONENTS	75,209	375	9,098	84,307	78,464	375	7,477	85,941	95,300	400			104,242	554	17,321	121,563
2.2 HELIUM CONTAINMENT VESSEL	26,647	131	2,372	29,019	26,846	131	2,780	29,626	28,846	131			8,155	683	24,885	33,040
3.1 COLD MASS SUBASSEMBLY PREP	6,145	128	2,923	9,068	6,145	128	2,898	9,043	34,061	613			6,493	295	12,120	18,613
3.2 20K HEAT SHIELD	7,668	159	3,704	11,372	7,468	159	3,851	11,319	18,756	120			8,030	184	6,500	14,530
3.3 80K HEAT SHIELD	18,254	150	3,679	21,933	18,253	157	3,613	21,866	8,957	108			10,573	245	18,139	28,712
3.4 UPPER VACUUM VESSEL	24,218	122	3,463	27,680	24,217	122	3,593	27,810	37,136	371			95,701	500	22,096	117,797
3.5 LOWER VACUUM VESSEL	12,354	105	4,371	16,694	12,356	105	3,787	16,143	13,301	371			7,851	315	13,207	21,058
3.6 VESSEL ENDS	3,400	100	2,500	5,900	3,400	100	2,510	5,910	0	0			1,693	308	14,893	16,586
4.1 INTERNAL BUS WORK	27,831	410	8,085	35,916	14,920	433	9,950	24,870	5,751	87			11,051	375	15,349	26,400
5.1 INTERCONNECTION ROUTING PARTS	10,073	105	5,014	15,087	30,190	105	4,250	34,440	49,100	0			27,337	0	0	27,337
5.2 SHIPPING/STORAGE/HANDLING	0	0	0	0	252	0	0	252	310	31			673	42	1,958	2,631
6.1 TESTING	0	0	0	0	0	67	1,546	1,546	0	461			0	0	0	0
6.2 WARM MAGNETIC MEASUREMENTS	0	31	577	577	0	67	1,546	1,546	0	0			0	64	2,503	2,503
6.3 COLD MAGNETIC MEASUREMENTS	1,250	40	1,344	2,594	1,260	34	773	2,033	0	0			0	7	158	158
6.4 CRYOGENIC TESTING FACILITY OPRNS.	0	0	0	0	0	34	773	773	0	0			0	0	0	0
8.1 DIRECT SHOP SUPPORT	0	0	0	0	0	0	0	0	0	250			13,117	0	0	13,117
8.2 MISCEL. AND INDIRECT SHOP SUPPORT	0	871	27,071	27,071	1,600	934	29,540	31,140	5,512	775			0	1,472	40,884	40,884
MATERIAL FACTORS & ALLOWANCES	15,363	0	0	15,363	16,000	0	0	16,000	94,118	0			0	0	0	0
ALLOWANCE FOR REJECTS	9,341	70	1,885	11,226	9,400	84	1,972	11,372	8,064	63			12,117	80	3,024	15,141
SUBTOTAL	587,781	4,716	123,407	711,188	640,460	4,633	133,520	773,980	745,804	5,114			700,035	5,069	215,595	915,630
TOTAL COST FOR TOOLING + DIPOLE MAGNETS	622,785	5,036	134,879	757,664	675,464	5,040	132,905	770,460	761,544	5,433			731,726	5,152	218,246	949,971
- ADDITIONAL FACTORS INCLUDED IN GD EST:																
OTHER COSTS - MAGNET FAB. RELATED (GD EST)																
PROJECT MANAGEMENT - DIRECT+CHECK SUPPORT										448						
QUALITY ASSURANCE PROGRAM										1,290						
TOOLING MAINT., MATL + LABOR									1,090	423						
SUBTOTAL (OTHER FAB RELATED)									1,090	2,160						
TOTAL - A + B + C									762,204	7,581	335,433	1,097,640				
OTHER "FACTORS AND ALLOWANCES" (GD EST)																
MATERIAL PROCUREMENT EXPENSES (ALLOWANCE)												56,300				
GRAPHICS/OVERTIME/TRAVEL ALLOWANCE												18,760				
FEE + COST OF MONEY ALLOWANCE												177,940				
SUBTOTAL (FACTORS/ALLOWANCES)												253,000				
									TOTAL COSTS=		[illegible]	1,350,640				

Table B–4.1

Design C Magnet Comparisons

Cost Per Each Dipole Magnet

TAC-CDG-GD-W comparisons 4

[illegible]

PER EACH DIPOLE MAGNET - STYLE C
[illegible]

WBS		LABORATORY ESTIMATE (TAC)				CENTRAL DESIGN GROUP ESTIMATE				GENERAL DYNAMICS ESTIMATE				WESTINGHOUSE ESTIMATE			
		MATL $	LBR HRS	LABOR $	TOTAL $	MATL $	LBR HRS	LABOR $	TOTAL $	MATL $	LBR HRS	LABOR $	TOTAL $	MATL $	LBR HRS	LABOR $	TOTAL $
	MAGNETS - DIRECT MATLS AND LABOR.							33.0									
1.1	COLD BORE TUBE	2171.3	22.0	462.0	2633.3	4735.0	42.1	668.3	5403.3	5391.0	44.3			3456.0	51.1	1200.0	4656.0
1.2	COILS	17403.0	84.0	1764.0	19167.0	15835.8	88.3	1843.7	17679.5	15835.0	88.6			17170.0	28.5	1000.0	18170.0
1.3					0.0				0.0							0.0	0.0
2.1	YOKE AND COMPONENTS	11458.0	105.5	2215.0	13673.0	12453.0	105.6	2458.7	14911.7	17500.2	127.4			13763.0	196.1	4831.6	18594.6
2.2	HELIUM CONTAINMENT VESSEL	2408.0	45.0	960.0	3368.0	1700.0	33.3	805.9	2505.9	1700.0	54.6			2150.0	33.0	940.1	3090.1
3.1	COLD MASS SUBASSEMBLY PREP (& CRYOSUP)	2254.6	4.5	95.0	2350.2	2264.0	33.0	759.0	3023.0	2719.2	8.5			1700.0	29.9	1099.1	2799.1
3.2	10K HEAT SHIELD	4697.5	3.5	73.5	4771.0	2457.3	58.0	1288.0	3745.3	3457.2	30.0			1200.0	17.5	663.0	1863.0
3.3	80K HEAT SHIELD		54.0	1134.0	1134.0	3632.4	10.0	230.0	3862.4	3830.4	20.0			1320.0	17.5	727.0	2047.0
3.4	VACUUM VESSEL	5931.2	15.2	315.5	6246.7	3855.2	61.0	1403.0	5258.2	6351.0	85.0			10460.0	92.1	3791.0	14251.0
3.5					0.0				0.0							0.0	0.0
3.6					0.0				0.0							0.0	0.0
4.1	INTERNAL BUS WORK				0.0	7300.0	40.0	920.0	8220.0	952.3	20.1			1550.0	45.3	1845.0	3395.0
5.1	INTERCONNECTION REGION PARTS				0.0	300.0			300.0	10830.0				2300.0		0.0	2300.0
5.2	SHIPPING/STORAGE/HANDLING				0.0	61.2	6.0	138.0	199.2	61.2	4.4			160.0	8.0	290.0	450.0
6.1	TESTING				0.0		8.0	184.0	184.0	0.0	136.0					0.0	0.0
6.2	WARM MAGNETIC MEASUREMENTS				0.0		16.0	368.0	368.0	0.0					10.6	480.4	480.4
6.3	COLD MAGNETIC MEASUREMENTS				0.0		8.0	184.0	184.0	0.0					1.3	30.1	30.1
6.4	CRYOGENIC TESTING FACILITY OPERNS.				0.0	150.0	8.0	184.0	334.0	0.0						0.0	0.0
8.1	DIRECT SHOP SUPPORT				0.0				0.0	0.0	30.0				225.1	7349.0	7349.0
8.2	MISCEL. AND INDIRECT SHOP SUPPORT		84.0	2688.0	2688.0	1600.0	125.0	3040.0	4640.0	3400.0						0.0	0.0
	MATERIAL FACTORS & ALLOWANCES				0.0	1500.0			1500.0	11047.5						0.0	0.0
	ALLOWANCE FOR REJECTS				0.0	1020.0	10.0	230.0	1250.0	1000.0	8.1			1090.0	8.0	311.5	1401.5
	SUBTOTAL	46134.3	418.5	9711.4	55845.7	57304.4	638.5	15784.6	73089.0	38774.5	658.7			55431.0	781.1	25048.4	80479.4

Table B—4.2

Design C Magnet Comparisons

Total Dipole Magnet Costs for Tooling and Full Production

* [illegible] comparisons 4

WBS	PER 4000 DIPOLE MAGNETS - DESIGN C ITEM	SSC COST ESTIMATE				CENTRAL DESIGN GROUP ESTIMATE				GENERAL DYNAMICS ESTIMATE				WESTINGHOUSE ESTIMATE			
		MAT'L K$	LAB HRS	LABOR K$	TOTAL K$	MAT'L K$	LAB HRS	LABOR K$	TOTAL K$	MAT'L K$	LAB HRS	LABOR K$	TOTAL K$	MAT'L K$	LAB HRS	LABOR K$	TOTAL K$
	TOOLING - DIRECT																0
4211. 1.1	COIL FABRICATION	15,000			15,000				0					2,391	11	265	0
1.2	YOKES, COLLARS, HE CONTR.				0				0					9,450	18	383	10,033
1.3	ELECTRICAL SYSTEMS				0				0								0
1.4	FINAL ASSEMBLY - CRYOSTAT				0				0					3,264			3,264
1.5	TESTING AND MEASUREMENTS				0				0					720			720
	SUBTOTAL (MAGNET "TOOLING" DIRECT)	$ 15,000	0	0	15,000	14,560	411	8,380	22,940	14,560	199			16,120	30	953	17,095
	MAGNETS - DIRECT MATLS AND LABOR																
4212 1.1	COLD BORE TUBE	8,485	83	1,848	10,333	18,940	108	2,073	21,013	21,560	177			13,000	285	5,932	18,932
1.2	COILS	68,012	338	7,056	75,068	63,740	301	7,375	71,115	63,740	333			68,005	158	4,373	72,403
1.3		0	0	0	0	0	0	0	0	0	0			0	0	0	0
2.1	YOKE AND COMPONENTS	45,875	433	8,880	54,695	48,812	438	9,835	58,647	50,831	540			53,100	513	10,566	63,666
2.2	HELIUM CONTAINMENT VESSEL	9,632	193	3,843	13,475	7,840	130	2,864	10,704	7,040	310			13,848	97	3,386	17,234
3.1	COLD MASS SUBASSEMBLY PREP (& SUPPORT)	9,058	19	382	9,441	9,058	132	2,836	12,094	10,877	28			6,980	195	4,116	11,096
3.2	10K HEAT SHIELD	10,700	14	294	10,994	9,870	234	5,104	14,984	9,897	114			5,398	75	2,516	7,914
3.3	80K HEAT SHIELD	0	216	4,135	4,135	14,530	45	900	15,430	14,530	114			5,158	39	2,885	8,043
3.4	VACUUM VESSEL	23,725	61	1,274	24,999	15,431	300	5,619	21,050	35,404	383			41,848	350	15,164	57,012
3.5		0	0	0	0	0	0	0	0	0	0			0	0	0	0
3.6		0	0	0	0	0	0	0	0	0	0			0	0	0	0
4.1	INTERNAL BUS WORK	0	0	0	0	29,530	160	3,400	33,200	2,800	80			6,224	101	2,303	8,527
5.1	INTERCONNECTION REGION PARTS	0	0	0	0	880	0	0	880	47,520	0			9,400	0	0	9,400
5.2	SHIPPING/STORAGE/HANDLING	0	0	0	0	345	24	352	697	345	18			640	32	1,190	1,830
6.1	TESTING	0	0	0	0	0	33	730	730	0	512			0	0	0	0
6.2	WARM MAGNETIC MEASUREMENTS	0	0	0	0	0	64	1,477	1,477	0	0			0	50	1,058	1,058
6.3	COLD MAGNETIC MEASUREMENTS	0	0	0	0	0	37	730	730	0	0			0	5	173	173
6.4	CRYOGENIC TESTING FACILITY OPERS.	0	0	0	0	400	33	730	1,130	0	0			0	0	0	0
8.1	DIRECT SHOP SUPPORT	0	0	0	0	0	0	0	0	0	107			0	800	20,364	20,364
8.2	SUPERV. AND INDIRECT SHOP SUPPORT	0	326	10,752	10,752	800	480	15,380	16,180	13,077	0			0	0	0	0
	MATERIAL FACTORS & ALLOWANCES	0	0	0	0	4,000	0	0	4,000	47,700	0			0	0	0	0
	ALLOWANCE FOR REJECTS	0	0	0	0	4,000	40	900	5,000	4,000	33			4,300	25	1,330	5,630
	SUBTOTAL	185,337	1,674	30,046	215,383	239,310	2,554	63,050	302,310	310,000	2,883			329,734	2,804	100,094	[illegible]
	TOTAL COST FOR TOOLING + DIPOLE MAGNETS	200,337	1,674	30,046	230,383	243,710	2,871	71,300	315,110	325,658	2,770			345,862	2,834	101,158	347,01
	- ADDITIONAL FACTORS INCLUDED IN GD EST:																
C	OTHER COSTS - MAGNET FAB. RELATED (GD EST)																
	PROJECT MANAGEMENT - DIRECT-ENGIN SUPPORT										327						
	QUALITY ASSURANCE PROGRAM										796						
	TOOLING MAINT., MATL + LABOR									870	280						
	SUBTOTAL (OTHER FAB RELATED)									870	1,316						
	TOTAL = A + B + C									330,528	4,090	175,854	506,370				
	OTHER "FACTORS AND ALLOWANCES" (GD EST)																
	MATERIAL PROCUREMENT EXPENSES (ALLOWANCE)												38,040				
	GRAPHICS/OVERTIME/TRAVEL ALLOWANCE												8,160				
	FEE + COST OF MONEY ALLOWANCE												61,180				
	SUBTOTAL (FACTORS/ALLOWANCES)												107,380				
										TOTAL COSTS =		[illegible]	613,750				

"C*" TAC-CDG comparisons 4

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Table B-5.1

Design C* Magnet Comparisons

Cost Per Each Dipole Magnet

PER EACH DIPOLE MAGNET - STYLE C* (1-IN-1)

(WBS)	ITEM	LABORATORY ESTIMATE (TAC) MATL $	LBR HRS	LABOR $	TOTAL $	CENTRAL DESIGN GROUP ESTIMATE MATL $	LBR HRS	LABOR $	TOTAL $
B	MAGNETS - DIRECT MATLS AND LABOR.							23.0	
14212. 1.1	COLD BORE TUBE	1085.6	11.0	231.0	1316.6	2367.5	21.0	483.0	2850.5
1.2	COILS	8701.5	42.0	882.0	9583.5	7958.0	42.1	922.3	8880.3
1.3					0.0				0.0
2.1	YOKE AND COMPONENTS	6997.2	79.5	1669.5	8666.7	7353.0	81.0	1863.0	9216.0
2.2	HELIUM CONTAINMENT VESSEL	3547.2	36.0	756.0	4303.2	2760.0	30.0	690.0	3450.0
3.1	COLD MASS SUBASSEMBLY PREP (& CRYOSUP)	1900.2	4.5	95.6	1995.8	1890.2	30.0	690.0	2580.2
3.2	10K HEAT SHIELD	4318.0	3.0	63.0	4381.0	2400.0	50.0	1150.0	3550.0
3.3	80K HEAT SHIELD		56.2	1180.6	1180.6	3600.0	8.0	184.0	3784.0
3.4	VACUUM VESSEL	4421.4	15.2	318.6	4740.0	5345.4	61.0	1403.0	6748.4
3.5					0.0				0.0
3.6					0.0				0.0
4.1	INTERNAL BUS WORK				0.0	3690.0	20.0	460.0	4150.0
5.1	INTERCONNECTION REGION PARTS				0.0	200.0			200.0
5.2	SHIPPING/STORAGE/HANDLING				0.0	61.2	6.0	138.0	199.2
6.1	TESTING				0.0		6.0	138.0	138.0
6.2	WARM MAGNETIC MEASUREMENTS				0.0		8.0	184.0	184.0
6.3	COLD MAGNETIC MEASUREMENTS				0.0		4.0	92.0	92.0
6.4	CRYOGENIC TESTING FACILITY OPERNS.				0.0	150.0	4.0	92.0	242.0
8.1	DIRECT SHOP SUPPORT				0.0				0.0
8.2	MISCEL. AND INDIRECT SHOP SUPPORT		61.0	1952.0	1952.0	100.0	84.0	2600.0	2700.0
	MATERIAL FACTORS & ALLOWANCES				0.0	800.0			800.0
	ALLOWANCE FOR REJECTS				0.0	510.0	5.0	115.0	625.0
	SUBTOTAL	30971.1	308.4	7148.3	38119.4	39705.3	460.1	11090.3	50497.6

"C*" TAC-CDG comparisons 4

Table B-5.2

Design C* Magnet Comparisons

Total Dipole Magnet Costs for Tooling and Full Production

8/07/85

(WBS)	PER 8000 DIPOLE MAGNETS - STYLE C* (1-IN-1) ITEM	TAC COST ESTIMATE MATL-K$	LBR KHRS	LABOR K$	TOTAL K$	CENTRAL DESIGN GROUP ESTIMATE MATL K$	LBR KHRS	LABOR K$	TOTAL K$
A	TOOLING - DIRECT								
14211. 1.1	COIL PRODUCTION	15,000			15,000				0
1.2	YOKES, COLLARS, HE CONTN.				0				0
1.3	ELECTRICAL SYSTEMS				0				0
1.4	FINAL ASSEMBLY - CRYOSTAT				0				0
1.5	TESTING AND MEASUREMENTS				0				0
	SUBTOTAL (MAGNET 'TOOLING' DIRECT)	$ 15,000	0	0	15,000	14,560	417	8,340	22,900
B	MAGNETS - DIRECT MATLS AND LABOR,								
14212. 1.1	COLD BORE TUBE	8,685	88	1,848	10,533	18,840	168	3,864	22,704
1.2	COILS	69,612	336	7,056	76,668	63,744	321	7,378	71,122
1.3		0	0	0	0	0	0	0	0
2.1	YOKE AND COMPONENTS	55,978	636	13,356	69,334	58,824	648	14,904	73,728
2.2	HELIUM CONTAINMENT VESSEL	28,378	288	6,048	34,426	22,080	240	5,520	27,600
3.1	COLD MASS SUBASSEMBLY PREP (& CRYOSUP)	15,202	36	765	15,966	15,202	240	5,520	20,722
3.2	10K HEAT SHIELD	34,544	24	504	35,048	19,200	400	9,200	28,400
3.3	80K HEAT SHIELD	0	450	9,445	9,445	28,900	64	1,472	30,372
3.4	VACUUM VESSEL	35,371	122	2,549	37,920	42,763	488	11,224	53,987
3.5		0	0	0	0	0	0	0	0
3.6		0	0	0	0	0	0	0	0
4.1	INTERNAL BUS WORK	0	0	0	0	29,520	160	3,680	33,200
5.1	INTERCONNECTION REGION PARTS	0	0	0	0	1,600	0	0	1,600
5.2	SHIPPING/STORAGE/HANDLING	0	0	0	0	490	48	1,104	1,594
6.1	TESTING	0	0	0	0	0	48	1,104	1,104
6.2	WARM MAGNETIC MEASUREMENTS	0	0	0	0	0	64	1,472	1,472
6.3	COLD MAGNETIC MEASUREMENTS	0	0	0	0	0	32	736	736
6.4	CRYOGENIC TESTING FACILITY OPERNS.	0	0	0	0	1,200	32	736	1,936
8.1	DIRECT SHOP SUPPORT	0	0	0	0	0	0	0	0
8.2	MISCEL. AND INDIRECT SHOP SUPPORT	0	487	15,616	15,616	880	877	21,504	22,384
	MATERIAL FACTORS & ALLOWANCES	0	0	0	0	6,400	0	0	6,400
	ALLOWANCE FOR REJECTS	0	0	0	0	4,080	40	920	5,000
	SUBTOTAL	247,769	2,467	57,186	304,955	313,642	3,605	90,339	403,981
	TOTAL COST FOR TOOLING + DIPOLE MAGNETS	262,769	2,467	57,186	319,955	328,202	4,022	98,679	426,881

APPENDIX C

MAGNET APERTURE SCALING FACTORS

In order to make the adjustment for required aperture, a study was made to examine the cost effect for a 1 cm aperture or gap perturbation for each of the magnet styles. An appropriate scaling factor at each "level 7" cost table entry was applied separately for materials and labor. Tables C-1 through C-5 show the individual scaling factors applied for each of the magnet styles. These individual factors for the cosine theta styles were obtained from a BNL program that was used to develop cosine theta costs for various magnet apertures. For the superferric styles, we used a geometric scaling relationship and aproximated the various entries accordingly.

The resulting total cost was then derived and used to determine a normalized overall aperture scaling factor for a 1.0 cm increase/decrease for each of the styles. The resulting overall aperture scaling factors are shown below for the dipoles.

Table C-6
Dipole Magnet Scaling Factors for a 1 cm Aperture Perturbation

Magnet Style:	A	B	D	C	C*
unadjusted aperture (cm)	4	5	4	2.54	2.54
perturbed aperture (cm)	5	4	5	3.54	3.54
Dipole Cost (unperturbed)	153023	59214	86190	73069	50498
Dipole Cost (perturbed)	179241	52672	100123	99030	67885
Dipole aperture cost factor	1.171	0.890	1.162	1.355	1.344

Table C-1
Style A - Magnet Aperture Scaling Factors
(FY85 $)

UNIT COSTS PER DIPOLE MAGNET

APERTURE SCALING FACTORS:

COS THETA STYLE A (4 CM REF)

CENTRAL DESIGN GROUP ESTIMATE

(WBS)		ITEM:	MATL $	LBR HRS	LABOR $	TOTAL $	MAT'L FACT	LABOR FACT	(5 CM) TOTAL $
C		MAGNETS - DIRECT MATLS AND LABOR							
14212.	1.1	COLD BORE TUBE	5273.0	68.5	1575.5	6848.5	1.25	1.00	8166.8
	1.2	COILS	65750.0	292.9	6736.7	72486.7	1.16	1.10	83516.8
	1.3	COIL COLLARING	12282.8	69.6	1600.8	13883.6	1.51	1.00	20111.0
	2.1	YOKE AND COMPONENTS	15870.0	43.6	1002.8	16872.8	1.27	1.05	21247.6
	2.2	HELIUM CONTAINMENT VESSEL	5444.6	15.6	381.8	5826.4	1.26	1.07	7268.5
	3.1	COLD MASS SUBASSEMBLY PREP	832.2	15.3	351.9	1184.1	1.02	1.02	1204.7
	3.2	20K HEAT SHIELD	912.9	18.9	434.7	1347.6	1.00	1.00	1347.6
	3.3	80K HEAT SHIELD	2558.4	18.7	430.1	2988.5	1.07	1.00	3172.7
	3.4	UPPER VACUUM VESSEL	3562.8	14.5	333.5	3896.3	1.09	1.00	4217.0
	3.5	LOWER VACUUM VESSEL	1744.6	19.6	450.8	2195.4	1.07	1.00	2317.5
	3.6	VESSEL ENDS	475.5	13.0	299.0	774.5	1.05	1.00	803.0
	4.1	INTERNAL BUS WORK	3553.7	103.0	2369.0	5922.7	1.00	1.00	5922.7
	5.1	INTERCONNECTION REGION PARTS	5000.0	22.0	506.0	5506.0	1.04	1.00	5706.0
	5.2	SHIPPING/STORAGE/HANDLING	30.0	0.0	0.0	30.0	1.00	1.00	30.0
	6.1	TESTING	0.0	8.0	184.0	184.0	1.00	1.00	184.0
	6.2	WARM MAGNETIC MEASUREMENTS	0.0	16.0	368.0	368.0	1.00	1.00	368.0
	6.3	COLD MAGNETIC MEASUREMENTS	150.0	8.0	184.0	334.0	1.00	1.00	334.0
	6.4	CRYOGENIC TESTING FACILITY OPERNS.	0.0	4.0	92.0	92.0	1.00	1.00	92.0
	8.1	DIRECT SHOP SUPPORT	0.0	0.0	0.0	0.0	1.00	1.00	0.0
	8.2	MISCEL. AND INDIRECT SHOP SUPPORT	200.0	180.0	5760.0	5960.0	1.00	1.00	5960.0
		MATERIAL FACTORS & ALLOWANCES	4000.0	0.0	0.0	4000.0	1.16	1.00	4640.0
		ALLOWANCE FOR REJECTS	2000.0	14.0	322.0	2322.0	1.16	1.00	2642.0
		TOTALS	129640.5	946.2	23382.6	153023.1			179240.9

5 CM/4 CM RATIO: 1.171

Table C-2
Style B - Magnet Aperture Scaling Factors
(FY85 $)

UNIT COSTS PER DIPOLE MAGNET

ITEM:

COS THETA STYLE B (5 CM REF)
CENTRAL DESIGN GROUP ESTIMATE

(WBS)	ITEM	MATL $	LBR HRS	LABOR $	TOTAL $	APERTURE SCALING FACTORS: MAT'L FACT	LABOR FACT	(4 CM) TOTAL $
	MAGNETS - DIRECT MATLS AND LABOR							
012. 1.1	COLD BORE TUBE	410.0	30.0	690.0	1100.0	.80	1.00	1018.0
1.2	COILS	23480.0	120.0	2760.0	26240.0	.86	.91	22791.4
1.3	COIL COLLARING	3341.0	30.0	690.0	4031.0	.86	1.00	3306.0
2.1	YOKE AND COMPONENTS	0.0	0.0	0.0	0.0	1.00	1.00	0.0
2.2	HELIUM CONTAINMENT VESSEL	2186.0	44.0	1012.0	3198.0	.79	.94	2683.9
3.1	COLD MASS SUBASSEMBLY PREP	7534.0	0.0	0.0	7534.0	.90	1.00	6780.6
3.2	20K HEAT SHIELD	2342.0	0.0	0.0	2342.0	.95	1.00	2224.9
3.3	80K HEAT SHIELD	1064.2	42.8	984.4	2048.7	1.00	1.00	2048.7
3.4	UPPER VACUUM VESSEL	0.0	31.4	722.2	722.2	1.00	1.00	722.2
3.5	LOWER VACUUM VESSEL	0.0	0.0	0.0	0.0	1.00	1.00	0.0
3.6	VESSEL ENDS	0.0	61.2	1407.6	1407.6	1.00	1.00	1407.6
4.1	INTERNAL BUS WORK	500.0	5.0	115.0	675.0	1.00	1.00	675.0
5.1	INTERCONNECTION REGION PARTS	2700.0	20.0	460.0	3160.0	.96	1.00	3057.4
5.2	SHIPPING/STORAGE/HANDLING	30.0	0.0	0.0	30.0	1.00	1.00	30.0
6.1	TESTING	0.0	8.0	184.0	184.0	1.00	1.00	184.0
6.2	WARM MAGNETIC MEASUREMENTS	0.0	8.0	184.0	184.0	1.00	1.00	184.0
6.3	COLD MAGNETIC MEASUREMENTS	150.0	4.0	92.0	242.0	1.00	1.00	242.0
6.4	CRYOGENIC TESTING FACILITY OPERNS.	0.0	4.0	92.0	92.0	1.00	1.00	92.0
8.1	DIRECT SHOP SUPPORT	0.0	0.0	0.0	0.0	1.00	1.00	0.0
8.2	MISCEL. AND INDIRECT SHOP SUPPORT	0.0	100.0	3200.0	3200.0	1.00	1.00	3200.0
	MATERIAL FACTORS & ALLOWANCES	1380.0	0.0	0.0	1380.0	.86	1.00	1186.0
	ALLOWANCE FOR REJECTS	675.0	7.0	161.0	836.0	1.00	1.00	836.0
	TOTALS	46460.2	515.4	12754.2	59214.4			52672.2

4 CM/5 CM RATIO: .890

Table C-3

Style D - Magnet Aperture Scaling Factors

(FY85 $)

UNIT COSTS PER DIPOLE MAGNET

(WBS)		ITEM:	COS THETA STYLE D (4 CM REF) CENTRAL DESIGN GROUP ESTIMATE MATL $	LBR HRS	LABOR $	TOTAL $	APERTURE SCALING FACTORS: MAT'L FACT	LABOR FACT	(5 CM) TOTAL $
C		MAGNETS - DIRECT MATLS AND LABOR							
14212.	1.1	COLD BORE TUBE	2636.0	34.3	788.9	3424.9	1.25	1.00	4083.9
	1.2	COILS	32875.0	146.5	3369.5	36244.5	1.16	1.10	41759.7
	1.3	COIL COLLARING	8141.0	34.8	800.4	8941.4	1.14	1.00	10054.9
	2.1	YOKE AND COMPONENTS	9341.0	38.7	890.1	10231.1	1.27	1.06	12823.5
	2.2	HELIUM CONTAINMENT VESSEL	3196.0	14.4	331.2	3527.2	1.26	1.07	4377.5
	3.1	COLD MASS SUBASSEMBLY PREP	803.0	15.0	345.0	1148.0	1.02	1.02	1168.0
	3.2	20K HEAT SHIELD	913.0	18.9	434.7	1347.7	1.00	1.00	1347.7
	3.3	80K HEAT SHIELD	2173.0	18.7	430.1	2603.1	1.07	1.00	2759.6
	3.4	UPPER VACUUM VESSEL	2883.0	14.5	333.5	3216.5	1.09	1.00	3476.0
	3.5	LOWER VACUUM VESSEL	1471.0	19.6	450.8	1921.8	1.07	1.00	2024.8
	3.6	VESSEL ENDS	415.0	13.0	299.0	714.0	1.06	1.00	738.9
	4.1	INTERNAL BUS WORK	1776.9	51.5	1184.5	2961.4	1.00	1.00	2961.4
	5.1	INTERCONNECTION REGION PARTS	3600.0	22.0	506.0	4106.0	1.04	1.00	4246.4
	5.2	SHIPPING/STORAGE/HANDLING	30.0	0.0	0.0	30.0	1.00	1.00	30.0
	6.1	TESTING	0.0	8.0	184.0	184.0	1.00	1.00	184.0
	6.2	WARM MAGNETIC MEASUREMENTS	0.0	8.0	184.0	184.0	1.00	1.00	184.0
	6.3	COLD MAGNETIC MEASUREMENTS	150.0	4.0	92.0	242.0	1.00	1.00	242.0
	6.4	CRYOGENIC TESTING FACILITY OPERNS.	0.0	4.0	92.0	92.0	1.00	1.00	92.0
	8.1	DIRECT SHOP SUPPORT	0.0	0.0	0.0	0.0	1.00	1.00	0.0
	8.2	MISCEL. AND INDIRECT SHOP SUPPORT	200.0	110.0	3520.0	3720.0	1.00	1.00	3720.0
		MATERIAL FACTORS & ALLOWANCES	2000.0	0.0	0.0	2000.0	1.16	1.00	2320.0
		ALLOWANCE FOR REJECTS	1120.0	10.0	230.0	1350.0	1.16	1.00	1529.2
		TOTALS	71723.9	585.9	14385.7	86109.6			100123.3
							5 CM/4 CM RATIO:		1.162

Table C-4
Style C - Magnet Aperture Scaling Factors
(FY85 $)

APERTURE SCALING FACTORS: MAT'L FACT LABOR FACT

UNIT COSTS PER DIPOLE MAGNET

ITEM: SUPERFERRIC STYLE C (2.54 CM GAP) (3.54CM GAP)
CENTRAL DESIGN GROUP ESTIMATE

(WBS)	ITEM	MATL $	LBR HRS	LABOR $	TOTAL $	MAT'L FACT	LABOR FACT	TOTAL $
C	MAGNETS - DIRECT MATLS AND LABOR							
1412. 1.1	COLD BORE TUBE	4735.0	42.1	968.3	5703.3	1.40	1.20	7791.0
1.2	COILS	15836.0	84.2	1943.7	17779.5	1.40	1.00	24153.0
1.3		0.0	0.0	0.0	0.0	1.00	1.00	0.0
2.1	YOKE AND COMPONENTS	12453.0	106.9	2458.7	14911.7	2.00	1.20	27856.4
2.2	HELIUM CONTAINMENT VESSEL	1760.0	33.3	765.9	2525.9	1.40	1.20	3383.1
3.1	COLD MASS SUBASSEMBLY PREP (& COVERUP)	2264.6	33.0	759.0	3023.6	1.20	1.20	3628.3
3.2	10K HEAT SHIELD	2457.2	56.0	1288.0	3745.2	1.20	1.00	4236.6
3.3	80K HEAT SHIELD	3632.4	10.0	230.0	3862.4	1.20	1.30	4658.9
3.4	VACUUM VESSEL	3855.2	61.0	1403.0	5258.2	1.40	1.20	7080.9
3.5		0.0	0.0	0.0	0.0	1.00	1.00	0.0
3.6		0.0	0.0	0.0	0.0	1.00	1.00	0.0
4.1	INTERNAL BUS WORK	7380.0	40.0	920.0	8300.0	1.00	1.00	8300.0
5.1	INTERCONNECTION REGION PARTS	200.0	0.0	0.0	200.0	1.20	1.00	240.0
5.2	SHIPPING/STORAGE/HANDLING	61.2	6.0	138.0	199.2	1.20	1.00	211.4
6.1	TESTING	0.0	8.0	184.0	184.0	1.00	1.00	184.0
6.2	WARM MAGNETIC MEASUREMENTS	0.0	16.0	368.0	368.0	1.00	1.00	368.0
6.3	COLD MAGNETIC MEASUREMENTS	0.0	8.0	184.0	184.0	1.00	1.00	184.0
6.4	CRYOGENIC TESTING FACILITY OPERNS.	150.0	8.0	184.0	334.0	1.00	1.00	334.0
8.1	DIRECT SHOP SUPPORT	0.0	0.0	0.0	0.0	1.00	1.00	0.0
8.2	MISCEL. AND INDIRECT SHOP SUPPORT	200.0	165.0	3840.0	4040.0	1.00	1.00	4040.0
	MATERIAL FACTORS & ALLOWANCES	1200.0	0.0	0.0	1200.0	1.00	1.00	1200.0
	ALLOWANCE FOR REJECTS	1020.0	10.0	230.0	1250.0	1.00	1.00	1250.0
	TOTALS	57304.4	638.5	15764.6	73069.0			99030.4

3.54 CM GAP/2.54 CM GAP: 1.355

Table C-5
Style C* - Magnet Aperture Scaling Factors
(FY85 $)

UNIT COSTS PER DIPOLE MAGNET

APERTURE SCALING FACTORS: MAT'L FACT, LABOR FACT

ITEM:

SUPERFERRIC STYLE C*(2.54 CM GAP)
CENTRAL DESIGN GROUP ESTIMATE

(3.54CM GAP)

(WBS)		ITEM	MATL $	LBR HRS	LABOR $	TOTAL $	MAT'L FACT	LABOR FACT	TOTAL $
C		MAGNETS - DIRECT MATLS AND LABOR							
14212.	1.1	COLD BORE TUBE	2367.5	21.0	483.0	2850.5	1.40	1.20	3894.1
	1.2	COILS	7968.0	40.1	922.3	8890.3	1.40	1.00	12077.5
	1.3		0.0	0.0	0.0	0.0	1.00	1.20	0.0
	2.1	YOKE AND COMPONENTS	7353.0	81.0	1863.0	9216.0	2.00	1.20	16941.6
	2.2	HELIUM CONTAINMENT VESSEL	2760.0	30.0	690.0	3450.0	1.40	1.20	4692.0
	3.1	COLD MASS SUBASSEMBLY PREP (& CRYOSUP)	1900.2	30.0	690.0	2590.2	1.20	1.20	3108.2
	3.2	10K HEAT SHIELD	2400.0	50.0	1150.0	3550.0	1.20	1.00	4030.0
	3.3	80K HEAT SHIELD	3600.0	8.0	184.0	3784.0	1.20	1.00	4504.0
	3.4	VACUUM VESSEL	5345.4	61.0	1403.0	6748.4	1.40	1.20	9167.2
	2.5		0.0	0.0	0.0	0.0	1.00	1.00	0.0
	3.6		0.0	0.0	0.0	0.0	1.00	1.00	0.0
	4.1	INTERNAL BUS WORK	3690.0	20.0	460.0	4150.0	1.00	1.00	4150.0
	5.1	INTERCONNECTION REGION PARTS	200.0	0.0	0.0	200.0	1.20	1.00	240.0
	5.2	SHIPPING/STORAGE/HANDLING	61.2	6.0	138.0	199.2	1.20	1.00	211.4
	6.1	TESTING	0.0	6.0	138.0	138.0	1.00	1.00	138.0
	6.2	WARM MAGNETIC MEASUREMENTS	0.0	8.0	184.0	184.0	1.00	1.00	184.0
	6.3	COLD MAGNETIC MEASUREMENTS	0.0	4.0	92.0	92.0	1.00	1.00	92.0
	6.4	CRYOGENIC TESTING FACILITY OPERNS.	150.0	4.0	92.0	242.0	1.00	1.00	242.0
	8.1	DIRECT SHOP SUPPORT	0.0	0.0	0.0	0.0	1.00	1.00	0.0
	8.2	MISCEL. AND INDIRECT SHOP SUPPORT	100.0	84.0	2688.0	2788.0	1.00	1.00	2788.0
		MATERIAL FACTORS & ALLOWANCES	800.0	0.0	0.0	800.0	1.00	1.00	800.0
		ALLOWANCE FOR REJECTS	510.0	5.0	115.0	625.0	1.00	1.00	625.0
		TOTALS	39205.3	458.1	11292.3	50497.6			67885.0

3.54 CM GAP/2.54 CM GAP: 1.344

APPENDIX D
DIPOLE MAGNET CONTINGENCIES

The following tables show the contingency factors that were developed for the various styles of the dipole magnets. Magnet Styles A, B, D, C, and C* are represented on Tables D-1 through D-5 respectively. The method used is to apply a separate contingency factor percentage to each detail "level 7" WBS category: individual factors were applied to material costs and labor costs. As will be noted in the tables, the percentage values ranged from 10% to 35%.

An individual assessment was made of the general design status and level of detail cost information available for each WBS entry. The lowest contingency values were assigned to the items fairly well developed and costed: superconducting cable unit costs (10%), lamination costs on a dollar per pound of steel and a per piece stamping cost basis, cryostat shield components, and vacuum vessel materials (15%). The highest costs were assigned to the overall labor (35% used for all of the labor in this study) to account for uncertainties in not only the direct labor quantities (hours) but also such variable factors as productivity factors, labor rate variations, etc. The tables show total contingency dollars calculated for each of the various magnet styles. At the bottom of each table a net effective contingency percentage is shown; this value is treated as an overall dipole magnet contingency factor and represents the weighted average of the individual factors applied directly.

Table D-1
Style A - Magnet Contingency Factors
(FY85 $)

		UNIT COSTS PER DIPOLE MAGNET					CONTINGENCY ANALYSIS MAT'L %	LABOR %	
		ITEM:	COS THETA STYLE A CENTRAL DESIGN GROUP ESTIMATE						
(WBS)			MATL $	LBR HRS	LABOR $	TOTAL $			CONTING$
C		MAGNETS - DIRECT MATLS AND LABOR.							
14212.	1.1	COLD BORE TUBE	5273.0	68.5	1575.5	6848.5	25	35	1869.7
	1.2	COILS	65750.0	292.9	6736.7	72486.7	10	35	8932.8
	1.3	COIL COLLARING	12282.8	69.6	1600.8	13883.6	25	35	3631.0
	2.1	YOKE AND COMPONENTS	15870.0	43.6	1002.8	16872.8	15	35	2731.5
	2.2	HELIUM CONTAINMENT VESSEL	5444.6	16.6	381.8	5826.4	15	35	950.3
	3.1	COLD MASS SUBASSEMBLY PREP	832.2	15.3	351.9	1184.1	25	35	331.2
	3.2	20K HEAT SHIELD	912.9	18.9	434.7	1347.6	15	35	289.1
	3.3	80K HEAT SHIELD	2558.4	18.7	430.1	2988.5	15	35	534.3
	3.4	UPPER VACUUM VESSEL	3562.8	14.5	333.5	3896.3	15	35	651.1
	3.5	LOWER VACUUM VESSEL	1744.6	19.6	450.8	2195.4	15	35	419.5
	3.6	VESSEL ENDS	475.5	13.0	299.0	774.5	15	35	176.0
	4.1	INTERNAL BUS WORK	3553.7	103.0	2369.0	5922.7	25	35	1717.6
	5.1	INTERCONNECTION REGION PARTS	5000.0	22.0	506.0	5506.0	25	35	1427.1
	5.2	SHIPPING/STORAGE/HANDLING	30.0	0.0	0.0	30.0	25	35	7.5
	6.1	TESTING	0.0	8.0	184.0	184.0	25	35	64.4
	6.2	WARM MAGNETIC MEASUREMENTS	0.0	16.0	368.0	368.0	25	35	128.8
	6.3	COLD MAGNETIC MEASUREMENTS	150.0	8.0	184.0	334.0	25	35	101.9
	6.4	CRYOGENIC TESTING FACILITY OPERNS.	0.0	4.0	92.0	92.0	25	35	32.2
	8.1	DIRECT SHOP SUPPORT	0.0	0.0	0.0	0.0	25	35	0.0
	8.2	MISCEL. AND INDIRECT SHOP SUPPORT	200.0	180.0	5760.0	5960.0	25	35	2066.0
		MATERIAL FACTORS & ALLOWANCES	4000.0	0.0	0.0	4000.0	25	35	1000.0
		ALLOWANCE FOR REJECTS	2000.0	14.0	322.0	2322.0	25	35	612.7
		TOTALS	129640.5	946.2	23382.6	153023.1			27674.7
							CONTING. %:		18.1

Table D-2
Style B - Magnet Contingency Factors
(FY85 $)

CONTINGENCY ANALYSIS

UNIT COSTS PER DIPOLE MAGNET

ITEM:

COS THETA STYLE B
CENTRAL DESIGN GROUP ESTIMATE

(WBS)		MATL $	LBR HRS	LABOR $	TOTAL $	MAT'L %	LABOR %	CONTING$
8	MAGNETS - DIRECT MATLS AND LABOR,							
1421. 1.1	COLD BORE TUBE	410.0	30.0	690.0	1100.0	25	35	344.0
1.2	COILS	23480.0	120.0	2760.0	26240.0	10	35	3314.0
1.3	COIL COLLARING	3941.0	30.0	690.0	4631.0	25	35	1226.8
2.1	YOKE AND COMPONENTS	0.0	0.0	0.0	0.0	15	35	0.0
2.2	HELIUM CONTAINMENT VESSEL	2186.0	44.0	1012.0	3198.0	15	35	682.1
3.1	COLD MASS SUBASSEMBLY PREP	7534.0	0.0	0.0	7534.0	25	35	1883.5
3.2	20K HEAT SHIELD	2342.0	0.0	0.0	2342.0	15	35	351.3
3.3	80K HEAT SHIELD	1064.2	42.8	984.4	2048.7	15	35	504.2
3.4	UPPER VACUUM VESSEL	0.0	31.4	722.2	722.2	15	35	252.8
3.5	LOWER VACUUM VESSEL	0.0	0.0	0.0	0.0	15	35	0.0
3.6	VESSEL ENDS	0.0	61.2	1407.6	1407.6	15	35	492.7
4.1	INTERNAL BUS WORK	560.0	5.0	115.0	675.0	25	35	180.2
5.1	INTERCONNECTION REGION PARTS	2700.0	20.0	460.0	3160.0	25	35	836.0
5.2	SHIPPING/STORAGE/HANDLING	30.0	0.0	0.0	30.0	25	35	7.5
6.1	TESTING	0.0	8.0	184.0	184.0	25	35	64.4
6.2	WARM MAGNETIC MEASUREMENTS	0.0	8.0	184.0	184.0	25	35	64.4
6.3	COLD MAGNETIC MEASUREMENTS	150.0	4.0	92.0	242.0	25	35	69.7
6.4	CRYOGENIC TESTING FACILITY OPERNS.	0.0	4.0	92.0	92.0	25	35	32.2
8.1	DIRECT SHOP SUPPORT	0.0	0.0	0.0	0.0	25	35	0.0
8.2	MISCEL. AND INDIRECT SHOP SUPPORT	0.0	100.0	3200.0	3200.0	25	35	1120.0
	MATERIAL FACTORS & ALLOWANCES	1380.0	0.0	0.0	1380.0	25	35	345.0
	ALLOWANCE FOR REJECTS	675.0	7.0	161.0	836.0	25	35	225.1
	TOTALS	46460.2	515.4	12754.2	59214.4			11996.6
					CONTING.%:			20.3

Table D-3
Style D - Magnet Contingency Factors
(FY85 $)

UNIT COSTS PER DIPOLE MAGNET

ITEM: COS THETA STYLE D
CENTRAL DESIGN GROUP ESTIMATE

(WBS)		MATL $	LBR HRS	LABOR $	TOTAL $	CONTINGENCY ANALYSIS MAT'L %	LABOR %	CONTING
C	MAGNETS - DIRECT MATLS AND LABOR,							
14212. 1.1	COLD BORE TUBE	2636.0	34.3	788.9	3424.9	25	35	935.1
1.2	COILS	32875.0	146.5	3369.5	36244.5	10	35	4466.8
1.3	COIL COLLARING	6141.0	34.8	800.4	6941.4	25	35	1815.4
2.1	YOKE AND COMPONENTS	9341.0	38.7	890.1	10231.1	15	35	1712.7
2.2	HELIUM CONTAINMENT VESSEL	3196.0	14.4	331.2	3527.2	15	35	595.3
3.1	COLD MASS SUBASSEMBLY PREP	803.0	15.0	345.0	1148.0	25	35	321.5
3.2	20K HEAT SHIELD	913.0	18.9	434.7	1347.7	15	35	289.1
3.3	80K HEAT SHIELD	2173.0	18.7	430.1	2603.1	15	35	476.5
3.4	UPPER VACUUM VESSEL	2883.0	14.5	333.5	3216.5	15	35	549.2
3.5	LOWER VACUUM VESSEL	1471.0	19.6	450.8	1921.8	15	35	378.4
3.6	VESSEL ENDS	415.0	13.0	299.0	714.0	15	35	166.9
4.1	INTERNAL BUS WORK	1776.9	51.5	1184.5	2961.4	25	35	858.8
5.1	INTERCONNECTION REGION PARTS	3600.0	22.0	506.0	4106.0	25	35	1077.1
5.2	SHIPPING/STORAGE/HANDLING	30.0	0.0	0.0	30.0	25	35	7.5
6.1	TESTING	0.0	8.0	184.0	184.0	25	35	64.4
6.2	WARM MAGNETIC MEASUREMENTS	0.0	8.0	184.0	184.0	25	35	64.4
6.3	COLD MAGNETIC MEASUREMENTS	150.0	4.0	92.0	242.0	25	35	69.7
6.4	CRYOGENIC TESTING FACILITY OPERNS.	0.0	4.0	92.0	92.0	25	35	32.2
8.1	DIRECT SHOP SUPPORT	0.0	0.0	0.0	0.0	25	35	0.0
8.2	MISCEL. AND INDIRECT SHOP SUPPORT	200.0	110.0	3520.0	3720.0	25	35	1282.0
	MATERIAL FACTORS & ALLOWANCES	2000.0	0.0	0.0	2000.0	25	35	500.0
	ALLOWANCE FOR REJECTS	1120.0	10.0	230.0	1350.0	25	35	360.5
	TOTALS	71723.9	585.9	14465.7	86189.6			16023.5
						CONTING. %:		18.6

Table 8-4
Style C - Magnet Contingency Factors
(FY85 $)

UNIT COSTS PER DIPOLE MAGNET ITEM (K$)	SUPERFERRIC STYLE C CENTRAL DESIGN GROUP ESTIMATE MATL $	LBR HRS	LABOR $	TOTAL $	CONTINGENCY ANALYSIS MAT'L %	LABOR %	CONTING
MAGNETS - DIRECT MATLS AND LABOR,							
[illegible] 1.1 COLD BORE TUBE	4735.0	42.1	968.3	5703.3	25	35	1522.7
1.2 COILS	15935.8	80.2	1843.7	17779.5	10	35	2238.9
1.3	0.0	0.0	0.0	0.0	25	35	0.0
2.1 YOKE AND COMPONENTS	12453.0	106.9	2458.7	14911.7	15	35	2728.5
2.2 HELIUM CONTAINMENT VESSEL	1760.0	33.3	765.9	2525.9	15	35	532.1
3.1 COLD MASS SUBASSEMBLY PREP (& CRYOSUP)	2264.6	33.0	759.0	3023.6	25	35	831.8
3.2 10K HEAT SHIELD	2457.2	56.0	1288.0	3745.2	15	35	819.4
3.3 80K HEAT SHIELD	3632.4	10.0	230.0	3862.4	15	35	625.4
3.4 VACUUM VESSEL	3855.2	61.0	1403.0	5258.2	15	35	1069.3
3.5	0.0	0.0	0.0	0.0	15	35	0.0
3.6	0.0	0.0	0.0	0.0	15	35	0.0
4.1 INTERNAL BUS WORK	7380.0	40.0	920.0	8300.0	25	35	2167.0
5.1 INTERCONNECTION REGION PARTS	200.0	0.0	0.0	200.0	25	35	50.0
5.2 SHIPPING/STORAGE/HANDLING	61.2	6.0	138.0	199.2	25	35	63.6
6.1 TESTING	0.0	8.0	184.0	184.0	25	35	64.4
6.2 WARM MAGNETIC MEASUREMENTS	0.0	16.0	368.0	368.0	25	35	128.8
6.3 COLD MAGNETIC MEASUREMENTS	0.0	8.0	184.0	184.0	25	35	64.4
6.4 CRYOGENIC TESTING FACILITY OPERNS.	150.0	8.0	184.0	334.0	25	35	101.9
8.1 DIRECT SHOP SUPPORT	0.0	0.0	0.0	0.0	25	35	0.0
8.2 MISCEL. AND INDIRECT SHOP SUPPORT	200.0	120.0	3840.0	4040.0	25	35	1394.0
MATERIAL FACTORS & ALLOWANCES	1200.0	0.0	0.0	1200.0	25	35	300.0
ALLOWANCE FOR REJECTS	1020.0	10.0	230.0	1250.0	25	35	335.5
TOTALS	57304.4	638.5	15764.6	73069.0			15037.6
					CONTING.%:		20.6

Table D-5
Style C* - Magnet Contingency Factors
(FY85 $)

UNIT COSTS PER DIPOLE MAGNET

ITEM:

CONTINGENCY ANALYSIS

SUPERFERRIC STYLE C*
CENTRAL DESIGN GROUP ESTIMATE

(WBS)		MATL $	LBR HRS	LABOR $	TOTAL $	MAT'L %	LABOR %	CONTINGS
C	MAGNETS - DIRECT MATLS AND LABOR,							
14212. 1.1	COLD BORE TUBE	2367.5	21.0	483.0	2850.5	25	35	760.9
1.2	COILS	7968.0	40.1	922.3	8890.3	10	35	1119.6
1.3		0.0	0.0	0.0	0.0	25	35	0.0
2.1	YOKE AND COMPONENTS	7353.0	81.0	1863.0	9216.0	15	35	1755.0
2.2	HELIUM CONTAINMENT VESSEL	2760.0	30.0	690.0	3450.0	15	35	655.5
3.1	COLD MASS SUBASSEMBLY PREP (& CRYOSUP)	1900.2	30.0	690.0	2590.2	25	35	716.5
3.2	10K HEAT SHIELD	2400.0	50.0	1150.0	3550.0	15	35	762.5
3.3	80K HEAT SHIELD	3600.0	8.0	184.0	3784.0	15	35	604.4
3.4	VACUUM VESSEL	5345.4	61.0	1403.0	6748.4	15	35	1292.9
3.5		0.0	0.0	0.0	0.0	15	35	0.0
3.6		0.0	0.0	0.0	0.0	15	35	0.0
4.1	INTERNAL BUS WORK	3690.0	20.0	460.0	4150.0	25	35	1083.5
5.1	INTERCONNECTION REGION PARTS	200.0	0.0	0.0	200.0	25	35	50.0
5.2	SHIPPING/STORAGE/HANDLING	61.2	6.0	138.0	199.2	25	35	63.6
6.1	TESTING	0.0	6.0	138.0	138.0	25	35	48.3
6.2	WARM MAGNETIC MEASUREMENTS	0.0	8.0	184.0	184.0	25	35	64.4
6.3	COLD MAGNETIC MEASUREMENTS	0.0	4.0	92.0	92.0	25	35	32.2
6.4	CRYOGENIC TESTING FACILITY OPERNS.	150.0	4.0	92.0	242.0	25	35	69.7
8.1	DIRECT SHOP SUPPORT	0.0	0.0	0.0	0.0	25	35	0.0
8.2	MISCEL. AND INDIRECT SHOP SUPPORT	100.0	84.0	2688.0	2788.0	25	35	965.8
	MATERIAL FACTORS & ALLOWANCES	800.0	0.0	0.0	800.0	25	35	200.0
	ALLOWANCE FOR REJECTS	510.0	5.0	115.0	625.0	25	35	167.8
	TOTALS	39205.3	458.1	11292.3	50497.6			10412.6
						CONTING. %:		20.6

APPENDIX E
REFERENCE DESIGNS STUDY COST COMPARISONS

The following tables show the cost comparisons for the magnet dependent systems for the various styles that are presented and compared in this report and the corresponding elements from the Reference Designs Study Cost Estimate (RDS Appendix C, May 1984).

Table E-1 shows the comparisons for the Magnet Systems Costs. It should be noted, however, that although both cost sections have been adjusted to FY1984 dollars for the comparison, the field level and aperture adjustments made for the present designs A, B, C, C*, and D do not correspond exactly to the same values in the RDS. The numbers of the dipole elements are slightly different, and in particular, the aperture for design B has been adjusted to 4.0 cm for the present cost comparisons, and it was formerly 5.0 cm in the RDS.

Table E-2 shows the Total Magnet Dependent Systems costs from the present study; Table E-3 shows the corresponding RDS values.

Table E-1
RDS Comparisons with Collider Magnet Systems
Adjusted Field Level
Adjusted Aperture
(FY84 K$)

	A	B	D	C	C*
ADJUSTED PARAMETER VALUES:					
ADJUSTED FIELD LEVEL, T	6.40	5.75	6.40	3.00	3.00
ADJUSTED NUMBER OF DIPOLES:	3,930	12,810	7,875	4,000	8,000
APERTURE, (DIA: A,B,D; GAP: C,C*),CM:	4.00	4.00	4.00	2.54	2.54
FIELD LEVEL/QUANTITY SCALING FACTOR:	.94	.96	.94	1.00	1.00
APERTURE SCALING FACTOR:	1.00	.89	1.00	1.00	1.00
ESCALATION SCALING FACTOR:	1.05	1.05	1.05	1.05	1.05
(* INDICATES ITEMS ADJUSTED)					
MAGNET SYSTEMS, WBS 1.4.2					
* TOOLING	41,497	23,738	41,497	21,810	21,810
* DIPOLE MAGNETS	573,837	642,937	646,421	278,358	304,744
* QUADRUPOLE MAGNETS	30,341	54,346	42,397	10,048	24,702
* SPEC. DEVICES/SPOOLS	37,543	75,818	67,674	84,567	110,067
* SPECIAL MAGNETS/INSERTIONS	14,286	14,286	14,286	14,286	14,286
* INSTALLATION & SURVEY	26,750	58,765	40,033	23,306	34,286
TOTAL MAGNET SYSTEMS:	732,254	869,890	853,309	441,473	589,95

REFERENCE DESIGNS STUDY COST COMPARISON: FY1984 K$	RDS A(84)	RDS B(84)	RDS C(84)
RREFERENCE DESIGNS STUDY PARAMETER VALUES:			
FIELD LEVEL, T	6.50	5.00	3.00
NUMBER OF DIPOLES:	3,870	14,880	990*
APERTURE, (DIA: A,B; GAP: C),CM:	4.00	5.00 *	2.54
MAGNET SYSTEMS, WBS 1.4.2			
TOOLING	38,504	21,290	14,979
DIPOLE MAGNETS	590,899	719,205	244,111
QUADRUPOLE MAGNETS	39,481	60,792	11,014
SPEC. DEVICES/SPOOLS	38,692	75,483	58,133
SPECIAL MAGNETS/INSERTIONS	11,241	20,000	6,430
INSTALLATION & SURVEY	35,673	58,505	7,825
GENERAL FACTORY SUPPORT (RDS A & C ONLY)	28,453	0	15,000
TOTAL MAGNET SYSTEMS:	782,953	955,275	357,492

Table E-2
Summary Cost Estimate
Magnet Dependent Systems
(FY84 K$)

	STYLE A	STYLE B	STYLE D	STYLE C	STYLE C*
CONSTRUCTION COSTS:					
ADJUSTED MAGNET SYSTEMS	732.25	869.89	853.31	441.47	589.95
OTHER TECHNICAL SYSTEMS	224.10	222.90	235.70	280.60	301.40
CONVENTIONAL SYSTEMS	410.38	444.15	410.38	761.70	761.70
SUBTOTAL: CONSTRUCTION	1,366.73	1,536.94	1,499.38	1,483.77	1,653.05
SYSTEMS ENGINEERING COSTS:					
MAGNET SYSTEMS	83.87	103.78	100.42	58.18	76.66
OTHER TECHNICAL SYSTEMS	42.50	43.00	44.70	55.80	59.70
CONVENTIONAL SYSTEMS	65.66	71.06	65.66	121.87	121.87
SUBTOTAL: SYS. ENGIN.	192.03	217.84	210.78	235.85	258.24
CONTINGENCY COSTS:					
MAGNET SYSTEMS	151.35	199.68	183.57	109.56	145.09
OTHER TECHNICAL SYSTEMS	49.70	49.80	52.30	62.80	67.40
CONVENTIONAL SYSTEMS	101.41	111.95	101.41	225.99	225.99
SYSTEMS ENGINEERING	48.01	54.82	52.69	65.06	70.65
SUBTOTAL: CONTINGENCY	350.47	416.24	389.98	463.40	509.13
TOTAL MAGNET SYS. DEPEND. COSTS	1,909.23	2,171.03	2,100.14	2,183.02	2,420.42

Table E-3
Summary Cost Estimate
Reference Designs Study
(FY84 K$)

	RDS A(84)	RDS B(84)	RDS C(84)
CONSTRUCTION COSTS:			
MAGNET SYSTEMS	782.95	955.27	357.49
OTHER TECHNICAL SYSTEMS	220.78	212.69	255.03
CONVENTIONAL SYSTEMS	398.65	496.11	733.49
SUBTOTAL: CONSTRUCTION	1,402.39	1,664.07	1,346.01
SYSTEMS ENGINEERING COSTS:			
MAGNET SYSTEMS	78.30	95.51	35.75
OTHER TECHNICAL SYSTEMS	42.21	40.98	47.43
CONVENTIONAL SYSTEMS	63.78	79.36	117.36
SUBTOTAL: SYS. ENGIN.	184.29	215.86	200.54
CONTINGENCY COSTS:			
MAGNET SYSTEMS	234.90	238.80	125.10
OTHER TECHNICAL SYSTEMS	48.00	47.10	55.70
CONVENTIONAL SYSTEMS	98.09	124.03	220.04
SYSTEMS ENGINEERING	90.45	98.76	83.39
SUBTOTAL: CONTINGENCY	471.44	508.69	484.24
TOTAL MAGNET SYS. DEPEND. COSTS	2,058.12	2,388.62	2,030.79

APPENDIX 9

FERMILAB MAGNET & CRYOSTAT DATA - August 5, 1985

Fermilab
Fermi National Accelerator Laboratory
P.O. Box 500 • Batavia, Illinois • 60510

August 5, 1985

Dr. J.D. Jackson
Lawrence Berkeley Laboratory
One Cyclotron Road
Mail Stop 90-4040
Berkeley, CA 94720

Dear Dr. Jackson:

Attached, as per M. Tigner's request of July 15, 1985, is a brief summary of the Fermilab SSC magnet model and study results for July, 1985. The summary includes 5 cm cosθ dipole coil test results and cryostat development.

Copies of the most recent conference papers; i.e., Cryogenic Engineering Conference (August 13-16, 1985), covering the following subjects will be forwarded to you on August 12, 1985:

- Thermal Shield Bowing
- Suspension Heat Leak Dewar
- Heatmeter
- Post Support
- Magnetic Effects Model
- Heat Leak Model
- Dipole Coil Properties

The papers treat significant details of the cryostat development program that will enhance the Magnet Selection Advisory Panel's understanding of the design concept.

Sincerely yours,

R.C. Niemann
Technical Support Section
Fermilab

Attachments

cc: (w/attachment)
H. Fisk
R. Lundy
P. Mantsch
M. Tigner

RECEIVED
SSC/CDG
AUG 7 1985
DIRECTORATE

Test Results on 5 cm Dipole Coils

To date five magnets have been tested warm, and four of these have been cold tested. The warm data include harmonics, and the cold data include quench performance and harmonics. The first three magnets - SG1003, SG1004, and SG1006 - are dry wound magnets constructed identically. SJ1003 is also a dry wound magnet with a modified design to achieve a reasonable sextupole moment. The first 5 cm molded (wet) coil, SK1001, has the same design as the SJ magnet series. This magnet is the next one to be cold tested.

Quench Performance

Figure 1 shows the quench performance for SJ1003. The other magnets perform similarly and show 7 to 10 quenches to reach the design field of 5.5 Tesla. Figure 2, which is an analog energy in-energy out curve for SJ1003, indicates almost no motion of the coil up to 4000 A, which may mean the training is occurring in the ends of the coil where the winding is not as well clamped as in the body region. Strain gauges are being installed in the new dry wound magnet models to make sure the coil is properly loaded. However, the lack of turn-up in this curve at high field is an indication the body of the coil is properly loaded.

Harmonics

The most recent warm measurements of multipoles are listed in Table I. In some cases they differ from previous measurements of the same magnets, especially a_1 and b_1, which are susceptible to feed down from the large sextupole:

$$(b_1 + ia_1)\ \mathrm{meas} = (b_1 + ia_1) + 2\ (b_2 + ia_2)\ (x_0 + iy_0)$$

where x_0 and y_0 are offset distances of the measurement coil with respect to the magnet axis. The numbers in the table are taken from measurements made with a new centering fixture that locates the coil to about 1/2 mm, which implies Δa_1 and Δb_1, of - 2 units. The estimated errors are given next to the values for magnet SG1003. The quadrupole moment errors for SK1001 and SJ1003 are correspondingly smaller due to the smaller sextupole moments.

There are cold harmonic data available for these magnets which are in the process of being reduced. The sextupole data for each magnet have been checked with warm measurements and there is good agreement. For example, the cold measurement of SJ1003 as shown in Figure 3 gives 6.6 units of normal sextupole at high excitation current (where persistent current effects are minimal) compared with 7.2 units for the warm measurement. It should be noted the cold and warm measurement coils have the same radius (1.47 cm) but differ in length by 6 in. (warm is 18 in. long, cold 12 in.).

The data in Table I are also shown in Figure 4 together with the Aperture Workshop predictions. The wet coil results are the dashed lines. At this point the preliminary conclusion would be that the Aperture Workshop conclusions are not too optimistic. With a sample of 10 magnets we will have a good idea of rms widths and then will only need to understani the length rms variation of multipoles (maybe Tom Collins knows the answer now).

Sextupole magnetization data for SJ1003 are shown in Figure 3 and for other magnets in our Vancouver paper (enclosed).

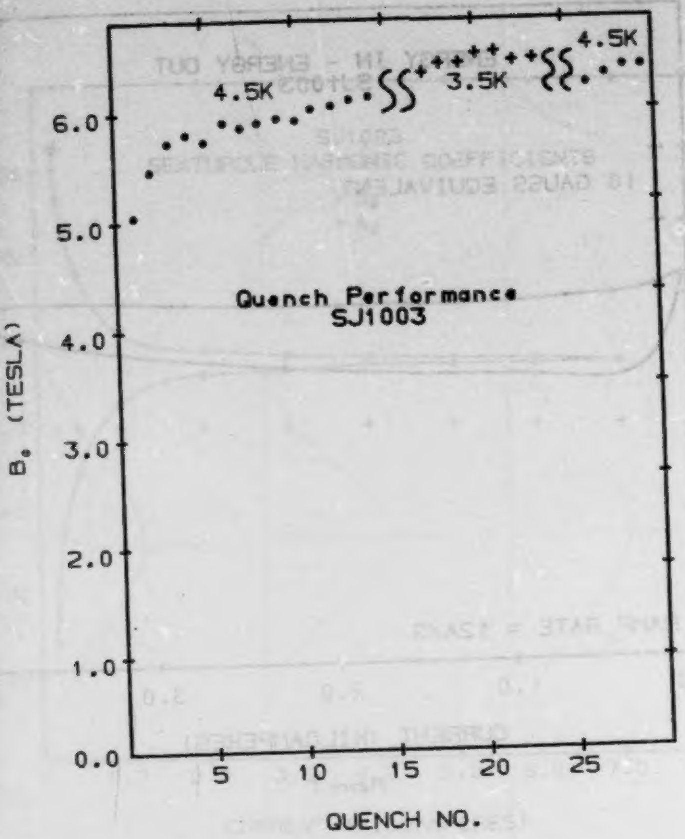
4.5K
4.5K
3.5K
Quench Performance
SJ1003
6.0
5.0
4.0
3.0
2.0
1.0
0.0
B₀ (TESLA)
5
10
15
20
25
QUENCH NO.

Figure 1

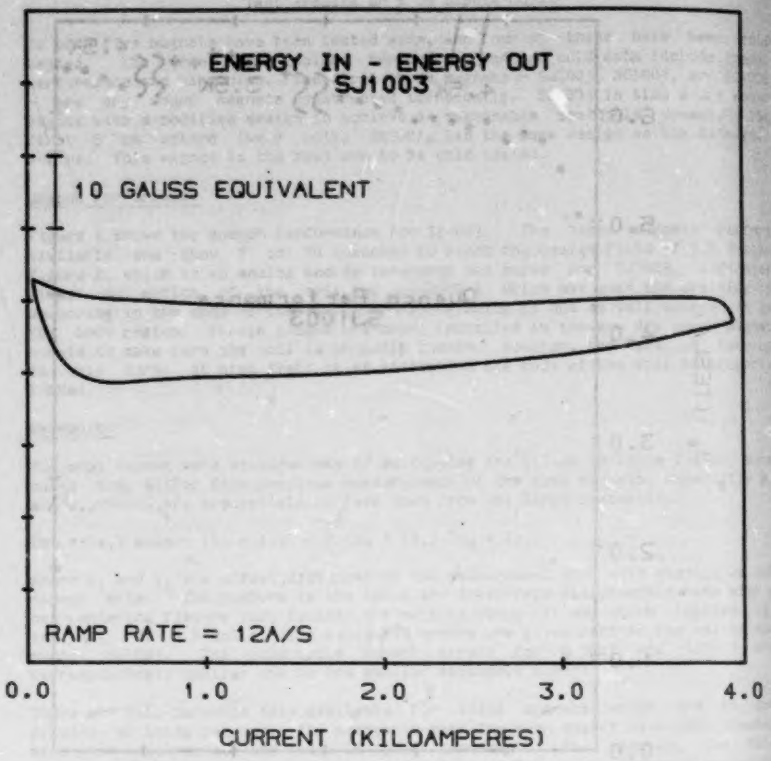
ENERGY IN - ENERGY OUT
SJ1003
10 GAUSS EQUIVALENT
RAMP RATE = 12A/S
0.0
1.0
2.0
3.0
4.0
CURRENT (KILOAMPERES)

Figure 2

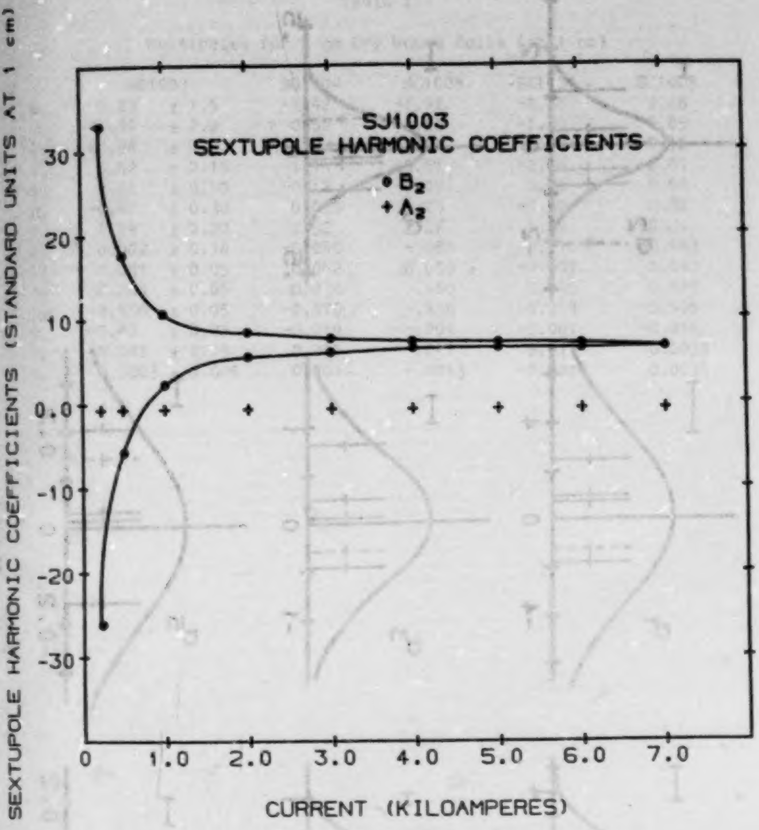
SJ1003
SEXTUPOLE HARMONIC COEFFICIENTS
● B_2
+ A_2
SEXTUPOLE HARMONIC COEFFICIENTS (STANDARD UNITS AT 1 cm)
30
20
10
0.0
-10
-20
-30
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
CURRENT (KILOAMPERES)

Figure 3

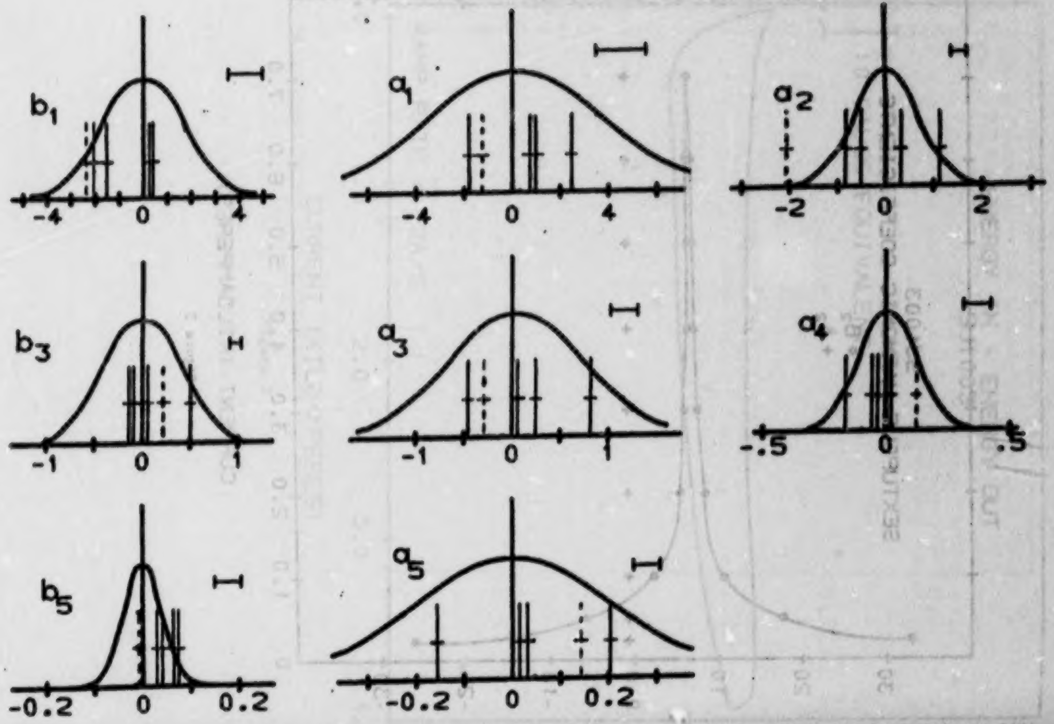

Figure 4

Table I

Multipoles for 5 cm Dry Wound Coils (at 1 cm)

	SG1003		SG1004	SG1006	SK1001	SJ1003
b_1	0.23	± 1.5	-1.42	-1.97	-2.36	0.26
a_1	-1.89	± 2.0	0.69	2.50	-1.30	0.85
b_2	42.98	± 0.5	43.44	43.74	15.58	7.16
a_2	0.42	± 0.15	1.14	-0.51	-2.06	-0.81
b_3	0.02	± 0.10	-0.12	-0.09	0.20	0.50
a_3	-0.47	± 0.30	0.035	0.25	-0.30	0.82
b_4	2.24	± 0.20	2.32	2.27	1.59	-0.20
a_4	0.002	± 0.10	-0.040	-.084	0.116	-0.163
b_5	0.031	± 0.05	0.062	0.059	-0.007	0.042
a_5	0.204	± 0.05	0.036	-.160	0.145	0.015
b_6	-0.456	± 0.05	-0.470	-.436	-0.314	-0.295
a_6	-0.02	± 0.02	-0.019	-.004	-0.007	-0.016
b_7	0.042	± 0.05	0.045	.047	0.014	0.0056
a_7	0.0003	± 0.005	0.001	-.0013	-0.0014	0.0031

THE IRONLESS Cosθ MAGNET OPTION FOR THE SSC

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Abstract

The Fermilab design of a 5 T, 5 cm aperture superconducting dipole is described, that attempts to integrate essential cryogenic details with a low cold mass, low heat leak magnet containing a coil surrounded by aluminum collars. Operating characteristics of coils made with aluminum collars are presented along with harmonic data obtained from 1 meter long 5 cm aperture collared coils. A summary of results obtained from cold tests of a 7.6 cm aperture, 6 m long aluminum collared coil in an iron vacuum vessel cryostat are reviewed. Results from the measurement of heat leak to 4.5K, 10K, and 80K are discussed for a 12 m prototype cryostat. Calculations are summarized for passively correcting the persistent current sextupole fields.

Introduction

There are a number of important requirements that need to be incorporated in the design of SSC magnets. Fortunately experience with the first large superconducting prototype synchrotron, the Tevatron, provides a good basis for making cost effective and technically wise decisions. Among the most important considerations are those having to do with: field level; magnet style, i.e. one in one or two in one; conductor specifications including filament size, copper to superconductor ratio and cable dimensions; coil cross section including aperture, number of layers of conductor, collar material and thickness; the use of iron for field shaping and increased central field; the magnet cooling scheme including the number of pipes and coolant channels and the use of intermediate temperature shields to intercept thermal radiation; the cryostat and mechanical support of the coil; the quench protection system; etc. The choice of alternatives, of course, must satisfy operational requirements having to do with field quality, cost, reliability, heat leak, quench performance and protection, etc.

Reference Design B, the ironless cosθ dipole differs in three significant ways from the other two options, A and C.[1] These differences are:

(1) one in one magnets;
(2) minimal iron;
(3) 5 cm aperture.

The rational for these choices is summarized as follows. The one in one magnet style choice, with the consequence of two separate rings, is based on several arguments, none of which by itself is overwhelming, but when taken as a whole seem to be best. With the side by side two in one magnet there is common flux through both apertures. Thus a quench in one aperture causes the other to quench or at least abort. Furthermore there are iron saturation effects that result in sextupole moment b_2 variation of several units from injection to full field, while other multipoles that vanish on average in the one in one case are usually present for two in one magnets. For the over and under, two in one magnets, where the magnet flux in the two apertures is not generally linked, the cryogenic operation may become difficult when one magnet aperture quenches and redirects flux to the cold aperture. In any case two in one magnets require iron and a Design B goal was to minimize iron and the consequent cold mass. One motivation for reduced cold mass was the time and/or refrigeration and power required to cool-down and warm-up.

The 5 cm aperture was selected to significantly reduce the amount of superconductor needed in SSC dipoles compared to that used in Tevatron dipoles. The basic goal is a cost reduction of 50% per unit length from the Tevatron experience. This factor is achieved by making the aperture smaller and the unit magnet length longer (few ends per unit length). Although the choice of a 5 cm aperture is not guaranteed to yield the quality of field that is required, the change from 7.6 to 5.0 cm is significant enough to make later adjustment to a different aperture an understandable task.

Design

A cross-sectional drawing of the Design B dipole is shown in Figure 1. The displayed section is cut through a support location to illustrate the first version of the post support used in constructing the Magnetic Effects Model magnet. The outer iron shell serves as a vacuum vessel and returns magnetic flux and also acts as a shield from leakage flux presented by the second ring.

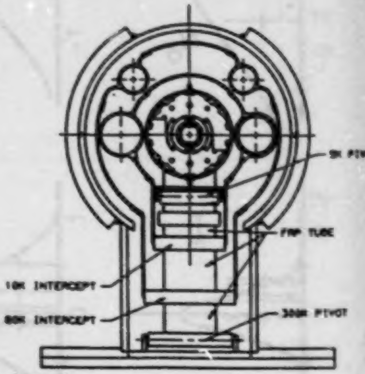

Figure 1 - Design B 5 cm Dipole Cross Section. The single phase assembly containing the aluminum collared coil is shown along with the 10K and 80K heat intercepts, G-10 support post, and external iron vacuum vessel.

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*Operated by Universities Research Assn. Inc., under contract with the U.S. Department of Energy.

There are two intermediate temperature shields, one at 80K (N_2) and one at 10K (He gas) each with their corresponding layers of super-insulation. The intermediate 10K shield (a slightly higher temperature may be desired) exists to intercept radiation from the 80K system that would otherwise end up in the 4.5K system, with a consequent saving in overall refrigeration costs. The cost effectiveness of this design is partially justified by the need to return gaseous He to the refrigeration system for re-liquefication. One optional pipe is shown that would be used if there were a decision to collide protons and anti-protons in a single magnet ring. This extra pipe would return N_2 if there were only a single ring. Further details that more fully describe the cryogenic system can be found in the Reference Design Report.[3]

The interior assembly that consists of the magnet coils, aluminum collars, and vacuum tight stainless steel skin around the collars is referred to as the single phase assembly. Inside the coil there is a cold beam pipe and there may be correction magnet windings in the single phase He flow channel between the coils and the beam tube.

The parameters that describe the single phase assembly and conductor are given in Table 1. Short sample measurements of the critical current for cables from reels 2674 (inner) and 2669 (outer) at 6T are 8100 A and 7375 A, respectively. The equivalent current densities are 1900 A/mm^2 at 6 T and about 2900 A/mm^2 at 5 T. These current densities are somewhat greater than was expected for high homogeneity NbTi superconductor.

Table 1
Reference Design B Parameters

Field(B min, B max)	0.25 T, 5.0 T
Maximum Current	6000 A
Aperture	5 cm
Collars	Aluminum 16.5 cm O.D.
Radial Collar Thickness	4.0 cm
Conductor Strand	0.75 mm diameter
Inner Cable(25 strands)	1.175 mm x 1.50 mm x 9.1 mm
Outer Cable(23 strands)	1.175 mm x 1.50 mm x 8.375 mm
Filament Diameter	17.5 μm
Cu/SC Ratio Inner	2.0 (1.8)
Cu/SC Ratio Outer	3.0 (1.8)

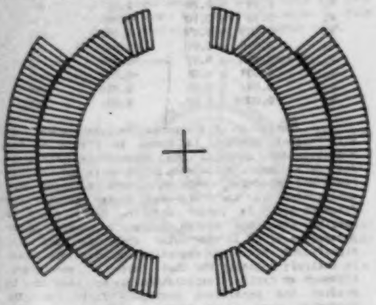


Figure 2 - Reference Design B Coil Configuration. The design employs a single Cu wedge in each quadrant on the inner turn.

Since the Rutherford style cable cannot be keystoned sufficiently to allow the cables to lie on radii of constant azimuth, copper wedges are installed in the winding as shown in Figure 2. This feature allows one to significantly reduce undesirable multipoles in the magnet design.

The aluminum collars surrounding the two layer coil are thick enough to permit the magnet to reach 6 T if further improvements are realized in the manufacture of superconductor. There are two major reasons for using Al collars instead of stainless steel. The use of Al would significantly reduce the magnet cost and the preload required to collar the coils is significantly less with Al since it shrinks more than stainless steel in the transition from room temperature to 4.5K.

To fully test the performance of Al collars, cable was procured with more superconductor than was indicated in the Design Report. This resulted in a Cu/SC ratio of 1.8 instead of the planned values of 2.0 and 3.0. To avoid the cost associated with procuring two different kinds of strand, both the inner and outer cable were fabricated from the same 0.030" diameter wire although the inner strand was pulled through a final die to slightly reduce its diameter.

Design B Prototypes

To judge the field quality and performance of Design B dipoles a number of short collared coil prototypes have been built and tested. The test magnets are 81 cm in over-all length. The scope of the R & D effort involves the construction of both 4 and 5 cm aperture magnets so that a comparison can be made of the field quality attainable in Designs B (5 cm) and D (4 cm).

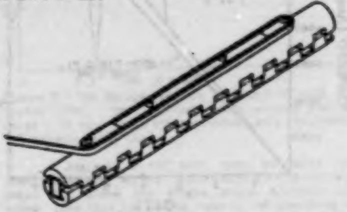


Figure 3 - Winding Mandrel. The split mandrel used to make the dry wound coils is shown.

The coil winding in the Fermilab models does not use epoxy impregnated fiberglass with subsequent heat treatment in a press to produce molded half coils. Instead the kapton insulated cable is wound onto a precisely dimensioned mandrel to form a coil that can then be collared immediately after winding. To facilitate the winding process the mandrel is vertically split open as shown in Figure 3 which allows turns to be inserted on the midplane of the magnet. Collaring is accomplished by placing collar packs over the coil and then simultaneously closing the mandrel and the collars. This results in a coil with conductors held in place solely by the collars without any epoxy. We refer to this type of coil winding as being a dry technique. Design B molded coils made with epoxy coated kapton but without fiberglass are also being constructed. They are known as wet coils.

Since superconducting cable with the Design B dimensions was not immediately available, two short dipoles, SC1001 and SJ1001 were built with non-standard conductor and cold tested. They performed adequately although specific changes in the tooling were indicated during the winding. Following the arrival of SSC conductor the winding of SG1001 and SG1002 commenced. Upon completion of SG1001 a turn to turn short was discovered and SG1002 was a failure because the bus turn pulled out of the coil as the winding mandrel was being extracted. With subsequent changes in the ground wrap insulation scheme four magnets have been successfully built. They are designated SG1003, SG1004, SG1006, and SJ1003.

SG1003, SG1004, and SG1006 have been cold tested and SJ1003 is awaiting cold tests. The cold tests include quench performance and measurement of harmonic field content in the body of the magnet. The load line for the high field point is shown in Figure 4 for SG1004 as well as the short sample performance of the cable that was used in the magnet. The magnet reached 6700A on the seventh quench at 4.2K and reached about 7100A at 4.2K after being cooled to 3.2K and quenched. With the expected 15% increase in J_c at 3.2K the high field point load line intercept with the anticipated short sample implies the magnet should reach 7500A. The maximum quench current at 3.2K was 7420A.

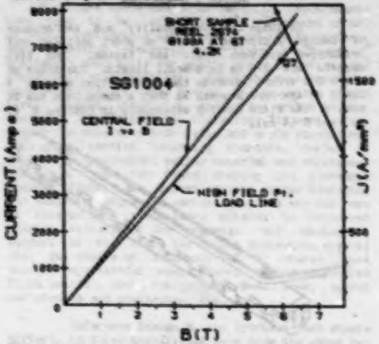


Figure 4 - Load Line, Conductor Short Sample and Magnet Performance for SG1004.

The harmonic content of the dipole's body field is given by the measured normal and skew coefficients in the expansion:

$$B_y + i B_x = B_0 \sum_{n=0} c_n z^n \text{ where}$$

$c_n = b_n + i a_n$ and $z = x + iy$. Both warm and cold measurements have been made to determine these coefficients. The cold results are found by rotating a Morgan coil at 6 Hz in the bore of the magnet and measuring the induced voltage at the harmonic frequency of interest. The voltage measurements are performed using either a magnetometer based on a Brookhaven design[3] or a lock-in amplifier. The warm measurements use a Morgan coil and lock-in amplifier, but in this case the induced voltage is generated by powering the magnet with 10A of 11 Hz alternating current. The voltage at a fixed Morgan coil angle is measured and recorded before the measuring coil is rotated to a new fixed angle position. The voltage recorded at 64 fixed positions (5.625° increments) is Fourier analysed to give the measured harmonic coefficients. A comparison of warm and cold harmonics for Tevatron dipoles and quadrupoles has shown good agreement as does the warm and cold data taken on the SSC prototypes. The warm measurement coefficients for SG1003, SG1004, and SG1006 are given in Table 2 and they are plotted in Figure 5. Also shown in Figure 5 are the predictions for 5cm aperture dipoles based on extrapolations from CBA (13.2 cm) and Tevatron magnets (7.6 cm).[4]

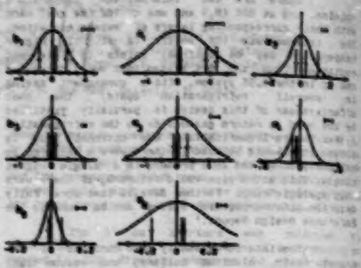


Figure 5 - Skew and Normal Multipoles. The values given in Table 2 are plotted here along with the SSC gaussian width predictions based on extrapolations of Tevatron and CBA dipole data.

Table 2

Multipoles for 5 cm Dry Wound Coils (at 1 cm)

	SG1003		SG1004	SG1006
b_1	1.60	± 1.5	-1.42	0.069
a_1	3.38	± 2.0	0.89	4.78
b_2	43.18	± 0.5	43.44	43.81
a_2	0.37	± 0.15	1.14	-.397
b_3	0.13	± 0.10	-0.12	.115
a_3	-0.11	± 0.30	0.035	.422
b_4	2.29	± 0.20	2.32	2.30
a_4	-0.10	± 0.10	-0.040	-.066
b_5	-0.009	± 0.05	0.062	-.007
a_5	0.016	± 0.05	0.036	-.165
b_6	-0.464	± 0.05	-0.470	-.433
a_6	0.004	± 0.02	-0.019	-.004
b_7	0.042	± 0.05	0.045	.046
a_7	0.0003	± 0.005	0.001	.0002

Variation of the normal sextupole moment b_2 with magnet current is shown in Figure 6. The magnetization currents are responsible for the sextupole moment difference of 20 units between full field and injection. This difference is larger than anticipated in the Reference Design because the filament size is larger and the Cu/SC ratio is smaller than the design calls for. The larger percentage of SC in the outer shell is especially significant since the magnetization sextupole moment is entirely negative for that layer of conductors. Although an explicit calculation has not been done to predict the persistent sextupole field for the conductor used in the magnet, the measurements when scaled by filament size and Cu/SC ratio are within 20% of Reference Design predictions. A specific comparison will be possible when measurements of the cable magnetization are complete.

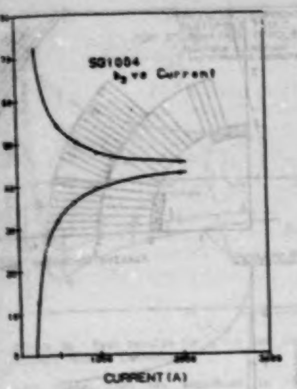


Figure 6 - Sextupole Hysteresis due to Persistent Currents.

Magnetic Effects Model

To test and prove the cryostat and vacuum vessel concepts embodied in the reference design a 6m long model was constructed.⁷ The features tested include: single phase assembly and cryostat construction techniques, support posts, off-centering forces, shield heating and deformation during quenching and general warm-up and cool-down procedures.

The magnet was specially equipped with carbon resistors for thermometry and linear variable differential transformers (LVDT) actuated by quartz rods that penetrated the insulating vacuum to measure single phase assembly and shield positions. A cross section showing the locations of three of the LVDTs is given in Figure 7. The LVDT sensitivity was about 1 mil. During cool-down and power tests the LVDT position and temperature were monitored with a Fast ADC system that accumulated data at a 10KHz rate.

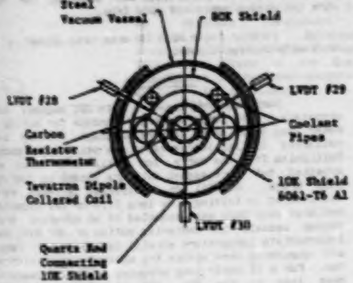


Figure 7 - LVDT Locations Relative to the Single Phase Assembly and Exterior Vacuum Vessel.

Figure 8 shows the response of the bottom LVDT on the 10K shield during a current extraction from the magnet without a quench. While calculations of induced eddy currents and subsequent deformation of the shields are difficult, due to the complicated shape of the shields with their component pipes, the predicted motion is for the shield to stretch vertically while it shrinks horizontally, to return to a circular configuration, and finally to stretch horizontally while shrinking vertically. Time constants are such that the first part of the motion just described is caused by the interaction of the decaying magnet current with the induced eddy currents while the later described motion results from eddy current interactions alone. If the shields are off center relative to the magnet coil the shields also translate slightly thus making the shield motion at a given point fairly complicated. Although there are not enough LVDTs to prove this is happening the data are consistent with such a hypothesis. The real situation is even more complicated since the shields are physically connected to the single phase assembly which moves because of magnetic off-centering forces.

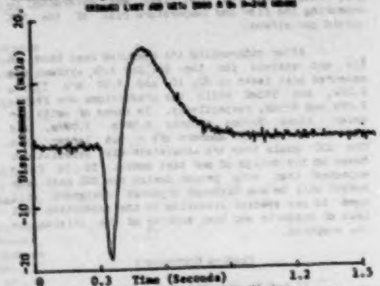


Figure 8 - 10K Shield Response as Measured with the Bottom LVDT. The vertical scale extends over the range ± 20 mils while the horizontal axis represents 1.5 seconds total time.

Analysis of the LVDT data indicates that when quenching occurs the shields flex elastically about 1mm. Since the single phase assembly also moves less than 1mm during ramping and quenching and returns to its original position one concludes there are no particular reasons for concern with Design B relative to off centering, eddy current caused shield deformation, shield heating during quenches, support post failure, etc.

Heat Leak Model

To achieve reasonable operating costs, the SSC magnets must have a small heat leak. The goal is a reduction to about one tenth (one fifth) the Tevatron static heat load at 4.5 (80)K. At this level the heat load due to synchrotron radiation ~2W/m will dominate the refrigeration load. While this goal is substantial, low heat leaks of 40 mW/m(5K) and 600 mW/m(80K) have been achieved in the Tevatron transfer lines compared to the Tevatron magnet system heat loads of 1.5 to 2.0 W/m(5K) and 7.5 W/m(80K), respectively. While it was not possible in the limited time available to specify and design the ultimate cryostat, testing an early prototype, to see if the goals were realistic, seemed to be necessary. Construction of a cryostat also allowed development of assembly procedures, mechanical engineering of support posts, tests of large multilayer insulation (MLI) thermal blankets, measurement of heat leak with variable insulating vacuum pressure, etc.

A 12m long thermal measurement model cryostat was designed and constructed. Since a 12m magnet coil was not available the 5K cold mass was faked by using a thick-walled aluminum cylinder of roughly equivalent size. The 5K and 80K thermal shields and their associated pipes were similar to those employed in the Magnetic Effects Model as were the support posts. Details of the geometry, insulation schemes, and preliminary results are given in the paper by Niemann et al.[7] To compensate for measurement effects due to the end cryogenic connection boxes, the end vessels were first butted together and sealed without the 12m model cryostat to determine the heat leaks of the end boxes alone. The 80K and 4.5K heat leaks of the fully assembled system (including the 12m cryostat and end boxes) were deduced by measuring the liquid N_2 and He boil-off to gas, while the 10K heat leak was determined by measuring the flow and temperature rise of the 10K shield gas stream.

After subtracting the measured heat load of the end vessels for the 80K and 4.5K systems the measured heat leaks at 80, 10, and 4.5K are 33.5W, 2.28W, and 510mW while the predictions are 29.5W, 2.28W and 425mW, respectively. In terms of watts per meter these become roughly 2.5W/m, 1.9W/m, and 39mW/m. While these numbers are ~ 50% larger than the SSC goals they are consistent with calculations based on the design of our test model. It is fully expected that with proper design the SSC heat leak budget will be met although cryostat designers will need to pay special attention to the conduction heat leak of supports and heat sinking of the shields to the supports.

Passive Correctors

It may be possible to avoid placing full length correction coils inside the SSC dipoles if the magnetization induced in strips of superconductor placed between the beam pipe and dipole coils can be used to cancel unwanted persistent current fields.[8]

The results of sample calculations are shown in Figure 9 for the Design D 4 cm aperture magnet. Since the magnetization sextupole moment generated by flux changes in the coil winding is negative, passive superconductor is placed in the regions ± 22.5° about the x and y axes. For the example where the Design D coil winding is made from 6μm filament wire with Cu/SC ratio 1.3 for the inner and 1.8 for the outer, the passive corrector can be about 2.5mm thick if its filaments are 8.7μm in diameter. A packing factor (metal area to total area) of 0.46 is assumed for the passive corrector to give this result as would be the case if insulated strands are used to make the corrections. Figure 9 also shows the normal sextupole field with and without the corrections.

A substantial cost saving may be possible if the passive superconductor can be imbedded in the outside of the beam pipe. Here it is assumed the passive superconductor can be drawn to make strips 3/4 mm thick and 3/4 cm wide with Cu/SC ratio 1.0 and packing factor 1.0. The beam pipe would be extruded with fins that collapse around the superconductor as both are drawn through a die to secure the superconductor.

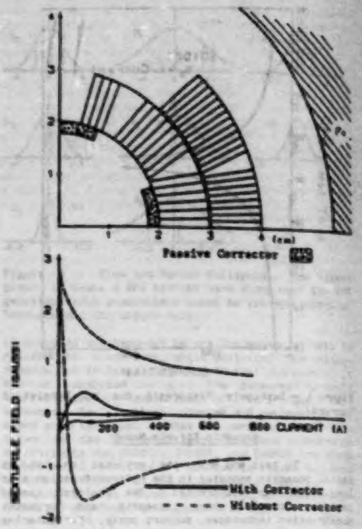


Figure 9 - Passive Correction Scheme & Predicted Sextupole Fields.

A test of the passive correction scheme was performed using a standard Tevatron cross section dipole and a corrector made from 20 mil insulated wire. The results are shown in Figure 10. With the corrector the sextupole field was reduced although not as much as desired. The reasons for the weakness of the corrector are: (1) the packing factor assumed in calculating the amount of corrector wire needed was 0.70 instead of the achieved value of 0.46; (2) the measured bulk magnetization of the corrector wire was about half the value that was measured for the wire the magnet cable was made from.

Further tests will be done with either a 4 or 5 cm prototype dipole.

Conclusions

Work has progressed on both SSC magnets and cryostats. The dry winding technique for making 1 meter long coils seems to work although winding and collaring tooling improvements are still being made. Multipoles from the early 5cm coils are about as expected but more magnet data are needed to confirm this trend. No ill or unexpected effects were encountered in testing a 6m long (7.6 cm ID) aluminum collared coil that was assembled in an external iron vacuum vessel. Off-centering motion of the coil and intermediate temperature shields during magnet ramps and quenching were within the nominal expectation of 1mm. For a 12 meter long cryostat model the measured heat leak to the 80K, 10K, and 4.5K systems was approximately what was anticipated and there is good reason to expect future designs to achieve the heat

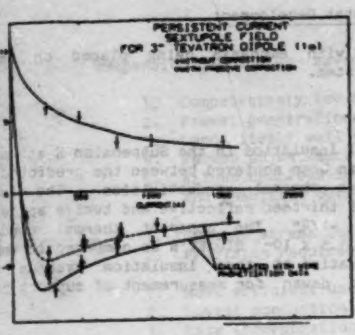


Figure 10 - Test Results for a 7.6 cm Coil with & Without Passive Correction.

leak budget that was suggested in the Reference Design Report. Activities over the next several months will center around construction of short coils of both 4 and 5cm inner diameter and the design of a 17m long cryostat that can accept a 4 or 5cm collared coil surrounded by cold iron.

References

[1] Superconducting Super Collider: Reference Designs Study for U.S. Department of Energy p 331 (May 8, 1984).

[2] C.H. Holbrow, An introduction to the Isabelle Harmonic Coil Magnetometer, Tech. Note 170 (1979) Brookhaven National Laboratory, Upton, New York.

[3] The predictions are the work of an Aperture Task Force subgroup on Magnet Errors; Jack Peterson, SSC Central Design Group, Lawrence Berkeley Laboratory.

[4] R.C. Niemann et al. "Experimental Evaluation of Design Features of a Cryostat for an Iron-less Cosθ SSC Magnet". Paper F28 of these proceedings.

[5] B.C. Brown and H.E. Fisk, "A Technique to Minimize Persistent Current Multipoles in Superconducting Accelerator Magnets". Proceedings of the 1984 Summer Study on the Design and Utilization of the Superconducting Super Collider, R. Donaldson & J.G. Morfin (ed). p 336 (1985).

Cryostat Development

Cryostat development has continued with emphasis being placed on heat leak measurements and the suspension system.

Heat Leak

The measurement of the proposed MLI insulation in the Suspension Heat Leak Dewar was completed. Good agreement has been achieved between the predicted and the measured insulation system apparent thermal conductivities. The insulation system consists of a blanket of thirteen reflective and twelve spacer layers having an installed thickness of ≈1/4". The apparent thermal conductivity between 300 and 80K as measured is 3.5×10^{-8} BTU/FT°R as compared to the design value of 3.6×10^{-8} BTU/FT°R. Evaluation of other insulation systems will be deferred to free the suspension dewar for measurement of support post heat leaks.

The measurements of the effectiveness of the thermal intercept linkage of the Magnetic Effects Model and Heat Leak Model began. The instrumented support post previously employed for heat leak measurements will be re-evaluated with intercept linkage identical to that of the two models. The purpose of the measurement is to confirm the shield to intercept ΔT as experienced in Magnetic Effects Model.

Suspension System

The advantages and disadvantages, thermal performance and stress-deflection values for the four major suspension system candidates were developed. The options considered were the compacted post, tension straps, compression strut and elliptical arch. The results are as given by Table I, II and III.

A folded post similar to that to be used in the first long design "D" magnets was fabricated. The posts will be tested in tension and compression at both 300 and 80K and in bending at 300K. A folded post is presently being instrumented for heat leak measurements in the suspension dewar.

The measurement of the creep characteristics of shrink fit joints continues. The joints have been at the simulated storage temperatures of 105°F for approximately two months. The creep vs time curve has reached its knee. At this point, predictions can be made of the long term creep of the material. The long term creep data will then be factored into analysis of the loss of force to slip for the shrink fit joint.

Work continued on the development of the test apparatus for measurement of creep of G10 tubes loaded in compression.

TABLE I

Review of Suspension Candidates- Advantages and Disadvantages

Compacted Post: Advantages	1. Competetively low heat leak. 2. Fewest penetrations in vacuum vessel. 3. Lends itself well to slide-in assembly. 4. Fewest adjustments at installation. 5. Allows complete internal assembly to be assembled and insulated outside the vacuum vessel.
Disadvantages	1. Highest stress levels during lateral loads. 2. Precision required for piece parts.
Tension Straps: Advantages	1. Most efficient use of material. 2. Lowest conduction heat leak. 3. Easy incorporation of shipping restraints.
Disadvantages	1. Many (approx. 18) penetrations in vacuum vessel, shields and MLI. 2. Large number of individual adjustments required. 3. Separate shield supports required. 4. Difficult to heat station. 5. Large self-weight deflection. 6. Largest potential thermal radiation heat leak.
Compression Struts: Advantages	1. Efficient use of material. 2. Potentially low heat leak.
Disadvantages	1. Many (approx. 18) penetrations in vacuum vessel, shields and MLI. 2. Large number of individual adjustments required. 3. Separate shield supports required. 4. Large self-weight deflection.
Elliptical Arch: Advantages	1. Insensitive to load direction (arch piece).
Disadvantages	1. Requires a lot of radial space. 2. Large 4.5K heat leak.

TABLE II

SSC Support Options- Heat Leak Summary

	80K (W)	WRT BUDGET (%)	20K (W)	WRT BUDGET (%)	4.5K (W)	WRT BUDGET (%)
Design Criteria, Rev "C" Budget + 25% of Allowed Contingency	5.570	-	0.490	-	0.091	-
Option 1: Compacted Post (5 Stations)	5.238	-5.96	0.494	+0.84	0.097	+6.59
Option 2: Tension Straps (4 stations)	3.866	-30.59	0.525	+7.14	0.040	-56.04
Option 3a: Compression Struts (G. D. Design Report w/uniaxial fiber in place of titanium) (4 stations)	8.574	53.93	0.684	+3959	0.094	+3.30
Option 3b: Compression Struts (R. Wolgast Drawings) (4 stations)	6.289	+12.91	-	-	0.571	-1.72 ($ calc from 20K +4K)
Option 4: Arch Support (5 stations)	6.086	+9.26	0.188	-61.63	0.253	+178.02

TABLE III

SSC SUPPORT OPTION - STRESS/DEFLECTION SUMMARY

	σ max @ 1g Vertical (psi)	σ max @ 0.7g Lateral (psi)	Support Deflection Due to Self Weight (in)
Option 1: Compacted Post	5000	32900	0.007
Option 2: Tension straps	10500	20700	0.028
Option 3a: Compression Struts	4500	6250	0.011
Option 3b: Compression Struts	4500	6250	0.009
Option 4: Arch Support	TBD	TBD	TBD

APPENDIX 10

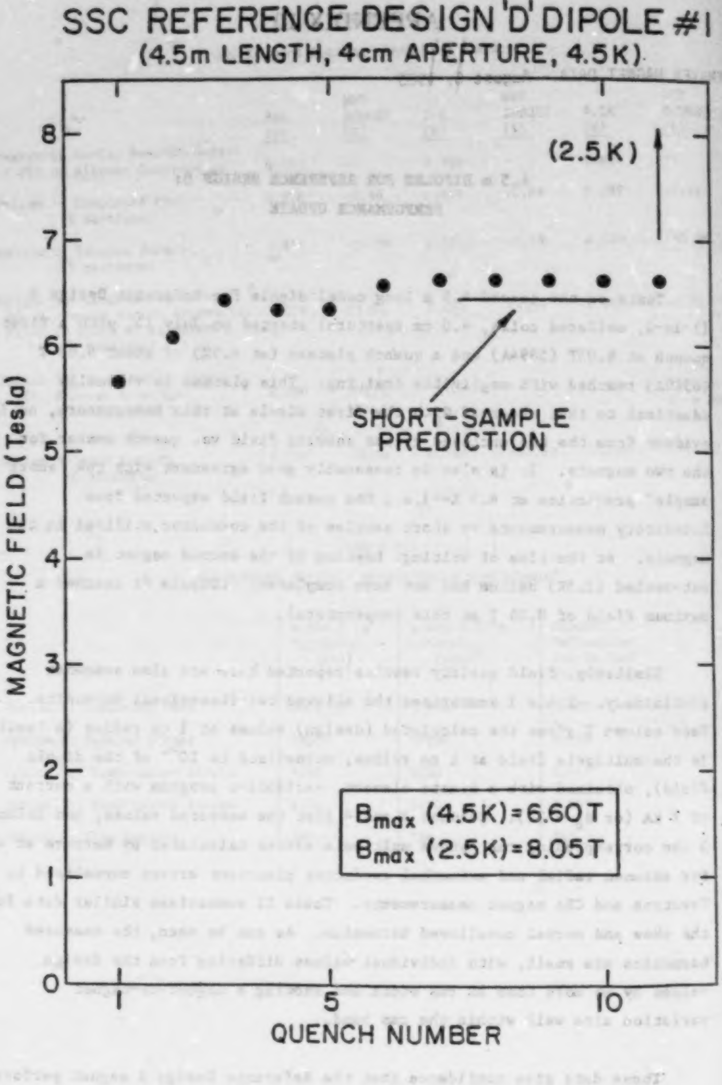
BROOKHAVEN MAGNET DATA - August 6, 1985

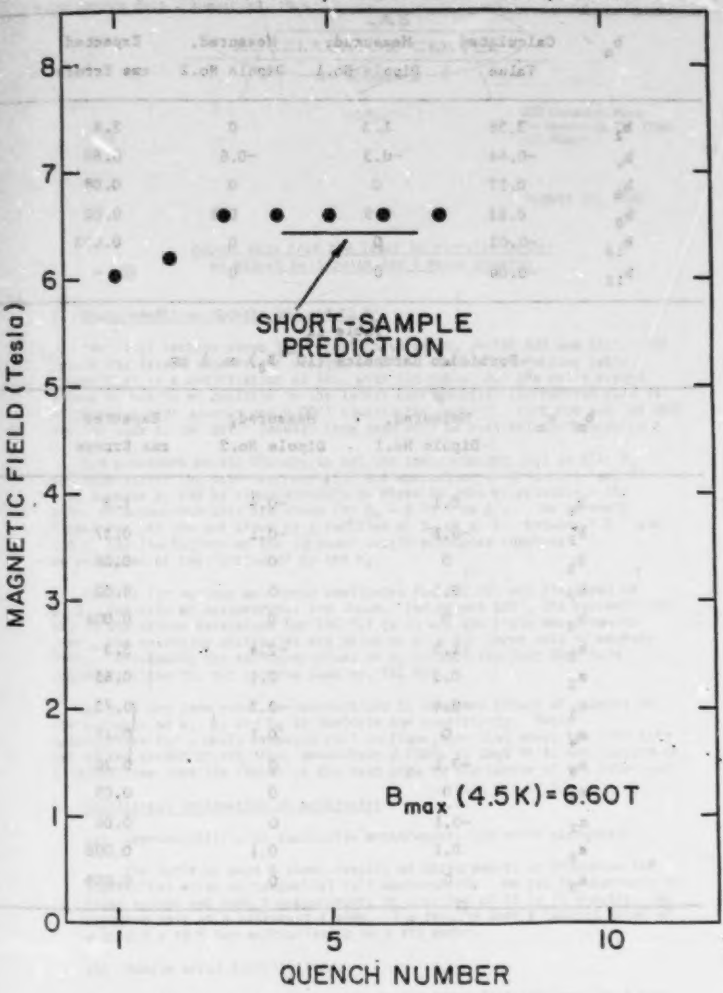
4.5 m DIPOLES FOR REFERENCE DESIGN D: PERFORMANCE UPDATE

Tests on the second 4.5 m long model dipole for Reference Design D (1-in-1, collared coils, 4.0 cm aperture) started on July 15, with a first quench at 6.03T (5894A) and a quench plateau (at 4.5K) of about 6.60 T (6520A) reached with negligible training. This plateau is virtually identical to that observed with the first dipole at this temperature, as is evident from the two enclosed graphs showing field vs. quench number for the two magnets. It is also in reasonably good agreement with the "short sample" prediction at 4.5 K—i.e., the quench field expected from laboratory measurements on short samples of the conductor utilized in the magnets. At the time of writing, testing of the second magnet in sub-cooled (2.5K) helium had not been completed. (Dipole #1 reached a maximum field of 8.05 T at this temperature).

Similarly, field quality results reported here are also somewhat preliminary. Table I summarizes the allowed two-dimensional harmonics. Here column 2 gives the calculated (design) values at 1 cm radius (a "unit" is the multipole field at 1 cm radius, normalized to 10^{-4} of the dipole field), obtained with a finite element, variable-μ program with a current of 2 kA (or $B_0 \sim 2T$). Columns 3 and 4 list the measured values, and column 5 the corresponding rms random multipole errors calculated by Herrera et al for assumed radial and azimuthal conductor placement errors normalized to Tevatron and CBA magnet measurements. Table II summarizes similar data for the skew and normal nonallowed harmonics. As can be seen, the measured harmonics are small, with individual values differing from the design values by no more than an rms width and showing a magnet-to-magnet variation also well within the rms band.

These data give confidence that the Reference Design D magnet performs well and that the tooling and techniques used in its construction promise to give magnet errors smaller than predicted from the older Tevatron and CBA results.


SSC REFERENCE DESIGN 'D' DIPOLE #1
(4.5m LENGTH, 4cm APERTURE, 4.5K)
MAGNETIC FIELD (Tesla)
QUENCH NUMBER
0
1
2
3
4
5
6
7
8
1
5
10
(2.5K)
SHORT-SAMPLE PREDICTION
B_{max} (4.5K)=6.60T
B_{max} (2.5K)=8.05T



SSC REFERENCE DESIGN 'D' DIPOLE #2
(4.5m LENGTH, 4 cm APERTURE, 4.5K)

Table I

Allowed Harmonics ($10^{-4} B_0$) at 1 cm

b_n	Calculated Value	Measured, Dipole No.1	Measured, Dipole No.2	Expected rms Errors
b_2	3.56	1.3	0	2.6
b_4	−0.44	−0.3	−0.6	0.68
b_6	0.17	0	0	0.08
b_8	0.83	0.9	0.8	0.02
b_{10}	−0.02	0	0	0.003
b_{12}	−0.04	0	0	-

Table II

Forbidden Harmonics ($10^{-4} B_0$) at 1 cm

b_n, a_n	Measured, Dipole No.1	Measured, Dipole No.2	Expected rms Errors
b_1	0.1	−0.4	1.8
b_3	−0.1	−0.1	0.57
b_5	0	0	0.06
b_7	0.1	0	0.02
b_9	0	0	0.004
a_1	−1.5	−2.4	3.3
a_2	0.3	0.1	0.65
a_3	−0.4	−0.3	0.73
a_4	0	0.1	0.15
a_5	−0.1	0	0.26
a_6	0	0	0.05
a_7	−0.1	0	0.04
a_8	0.1	0.1	0.008
a_9	0	0	0.009

APPENDIX 11

:AS
ACCELERATOR CENTER

2319 Timberloch Place
The Woodlands, TX 77380
(713) 363-0121

August 15, 1985

Recent Data from the Texas Accelerator Center on Magnet Multipoles for 1 Meter Dipoles

1. Measurements on Magnets 007 and GD 1'

The first section shows the recent measurements on TAC 007 and GD1'. TAC 007 is the latest superferric design, with the new superconducting cable. Magnet GD1' is a modification of GD1, with old cable, but the coils repositioned as nearly as possible in the latest configuration (correction coil is displaced 0.020" upwards and 0.007" towards the center). (TAC 008 and TAC 009 are the same as TAC 007. Results from them will be available on August 25.)

The procedure on TAC 007 was to set the inner current (I_i) to give B_0 and then adjust the outer current (I_0) and correction or trim coil current (I_t) to make b_2 and b_4 simultaneously as close to zero as possible. The steps to accomplish this are shown for B_0 = 3.03 T on p.3. The currents needed for TAC 007 are shown as a function of B_0 on p. 4. Between 1.0 T and 2.0 T, the limitations of the I_o power supply prevented complete optimization of the zeroing of b_2 and b_4.

Results for various multipole amplitudes for TAC 007 are displayed on p. 5. Two sets of measurements are shown. For magnet GD1', the currents are set at the values determined for TAC 007 (p.4) and the field measurements made. The resulting multipoles are shown on p. 6 for three sets of measurements. Presumably the non-zero values of b_2 reflect the fact that this magnet is close to, but not the same as, TAC 007.

On p. 7 are some notes on calculations to show the effect of changes in the currents on B_0, b_2 and b_4 to indicate the sensitivity. These matrices are for a newly proposed coil configuration that moves the trim coil out of the corner of the iron, down about 0.050", so that it is not located on a radial line from the center of the beam pipe to the center of the outer coil.

2. Statistical information on multipoles

(a) Reproducibility of successive measurements and error assignment:

The table on page 8 shows results of measurements to determine the statistical error on tangential coil measurements. We set the currents to fixed values and made 5 measurements in a period of 10 to 15 minutes. We repeated this at 6 different fields. The results show a typical error of $\sigma \cong 0.3 \times 10^{-4}$ for multipoles up to sixth order.

(b) Random error distributions:

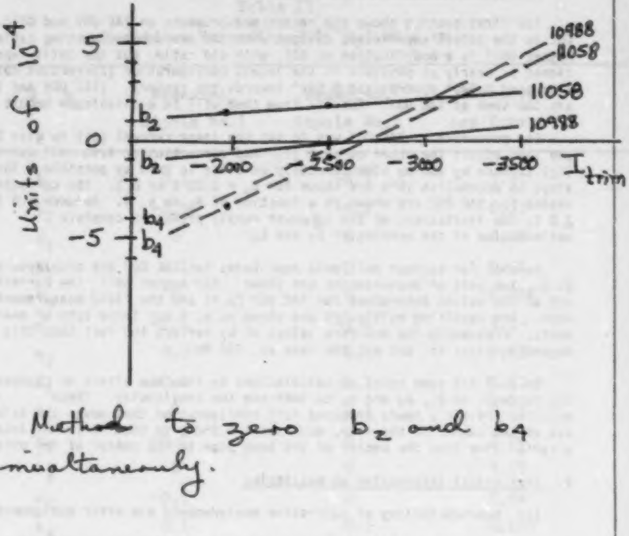
The figures on page 9 show the random error distributions for 8 magnets. The data for these plots are shown on page 10. We chose data points in the region of $B_0 \simeq 1.4\text{-}2.0$ T.

(Summary prepared by JDJ)

Data 8/10/85 3

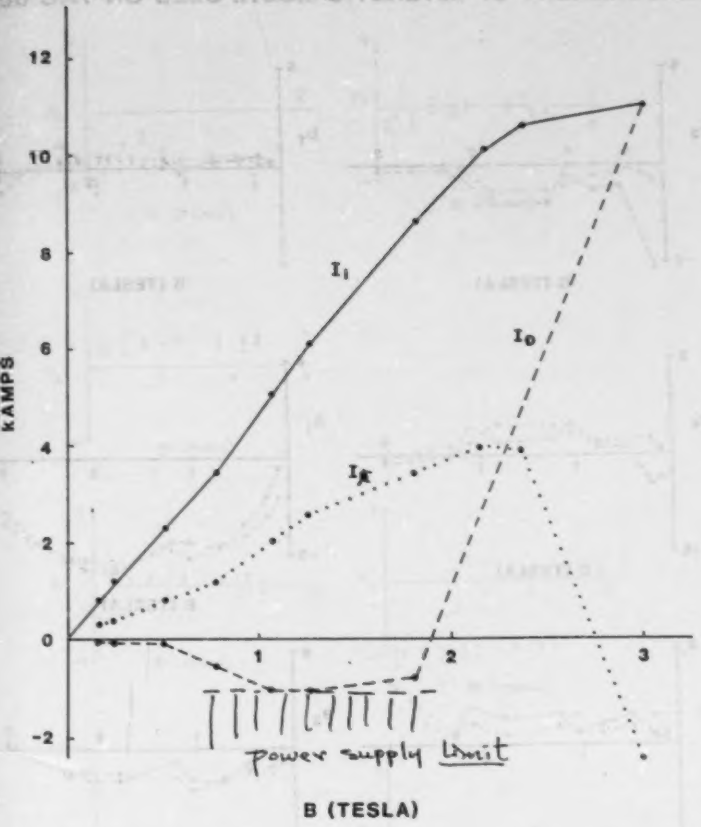
At 3.03 T

$I_G - I_{out}$	I_{trim}	a_1	b_2	a_2	b_4	a_3	b_6
11058	−1988	−2.3	1.4	.9	−3.4	−.1	1.9
11057	−2500	−3.0	1.8	1.3	−.9	−.5	2.3
10988	−2502	−2.5	−.2	.8	−.3	.4	3.3

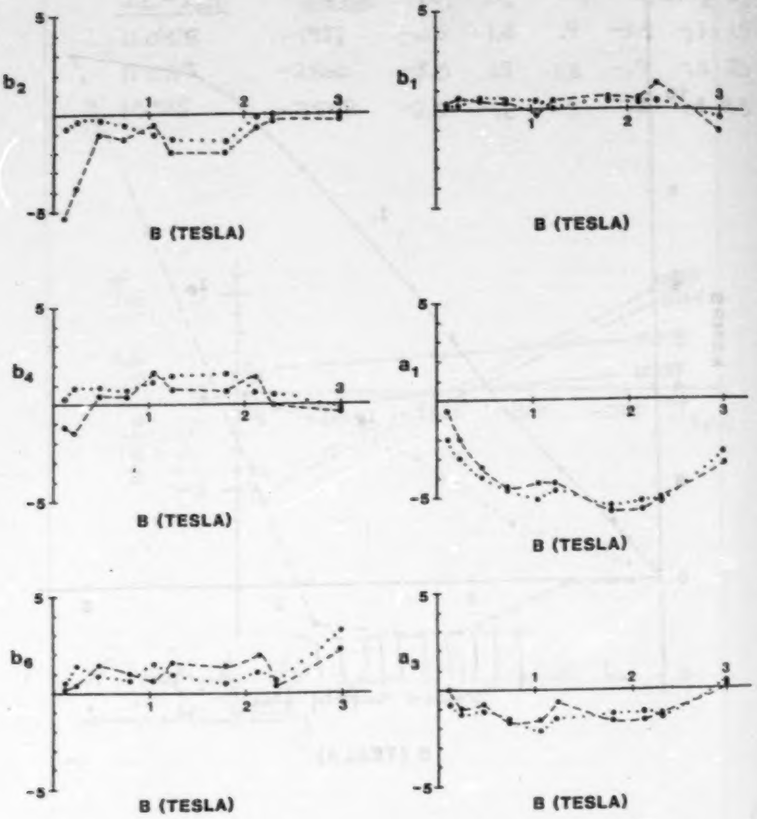


Method to zero b_2 and b_4 simualtaneouly.

CURRENTS TO ZERO b_2 AND b_4 IN TAC 007



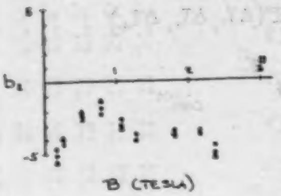
MEASUREMENT OF MAGNETIC MULTIPOLES ON TAC 007

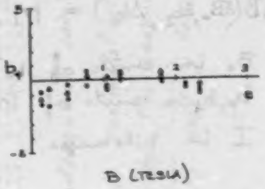


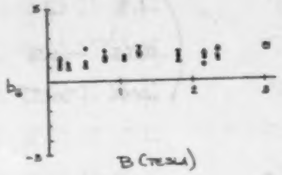
ALL DATA ARE FROM A 1 ft. LONG MEASUREMENT COIL CENTERED ALONG A MAGNET

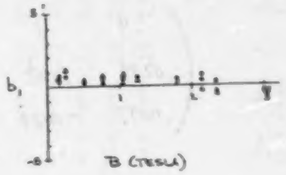
6

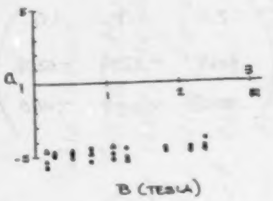
MEASUREMENT OF MAGNETIC MULTIPOLES ON MAGNET G01'
(with currents from TAC 007)

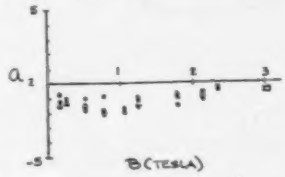


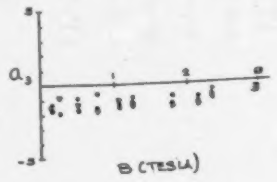












Matrix to Change $b_2 + b_4$

(new design – after 9/1/85)

$$\Delta B(\Delta B_0, \Delta b_2, \Delta b_4) = M\,\Delta I(\Delta I_1, \Delta I_0, \Delta I_4)$$

B_0 in units of 10^{-4} T

b_2, b_4 in units of 10^{-4} cm^{-n}

I in kiloamps.

B_0 = .5079 T

$$\begin{pmatrix} 1.98 & 1.96 & .98 \\ .0215 & -.0614 & -.0508 \\ .0108 & -.0305 & -.0271 \end{pmatrix}$$

B = 2.409 T

$$\begin{pmatrix} 1.3 & 1.1 & .6 \\ .0263 & -.0056 & .0019 \\ .0046 & -.0437 & -.0040 \end{pmatrix}$$

B_0 = 1.253 T

$$\begin{pmatrix} 2.0 & 1.9 & 1.0 \\ .0068 & -.0294 & -.0208 \\ .0038 & -.0139 & -.0110 \end{pmatrix}$$

B = 3.000

$$\begin{pmatrix} .9 & .7 & .5 \\ .0278 & .0002 & .0054 \\ .0097 & -.0024 & -.0028 \end{pmatrix}$$

STATISTICAL error on measurements σ ~ 0.3-0.4

601 Run 25486

$\times 10^{-4}$

I_{in}	I_T	I_{off}	B_0	b_1	b_2	b_3	b_4	b_5	b_6	a_1	a_2	a_3	a_4	a_5	a_6
557.5	13.2	27.4	0.0786	1.0 ±0.3	-0.1 0.6	0.1 0.2	3.4 0.4	-0.1 0.2	1.4 0.4	1.1 0.2	-2.6 0.2	-0.4 0.3	-0.3 0.3	-0.5 0.6	0.6 <> 0.2 σ
634.6	54.0	78.1	0.1376	0.0 ±0.3	-1.0 0.3	-0.2 0.3	0.3 0.2	-0.2 0.3	1.6 0.1	-1.4 0.3	-2.3 0.1	-0.7 0.4	0.6 0.3	-0.4 0.4	0.3 <> 0.6 σ
2143.3	395.9	212.1	0.5076	0.3 ±0.2	-2.4 0.3	-0.3 0.3	-1.3 0.2	0.0 0.3	0.9 0.3	-1.6 0.3	-1.5 0.2	-0.4 0.3	-0.2 0.3	0.1 0.4	0.4 <> 0.4 σ
4570.8	725.3	431.9	1.0701	0.4 ±0.1	-0.4 0.4	-0.3 0.2	0.5 0.3	-0.2 0.1	1.3 0.3	-2.5 0.3	-1.2 0.1	-1.6 0.2	0.0 0.3	-0.2 0.5	0.4 <> 0.2 σ
6054.4	985.1	450.8	1.3906	0.3 ±0.4	-0.1 0.3	-0.6 0.3	1.4 0.4	0.0 0.4	1.4 0.4	-2.2 0.1	-1.5 0.2	-0.7 0.3	-0.3 0.4	0.3 0.3	0.1 <> 0.2 σ
8075.4	1691.0	102.6	1.7810	0.5 ±0.1	-0.4 0.1	-1.0 0.3	2.8 0.3	-0.7 0.3	2.0 0.3	-2.5 0.3	-1.2 0.1	-0.9 0.3	0.0 0.2	0.1 0.2	-0.1 <> 0.3 σ

I_{in}	I_T	I_{off}	B_0	b_1	b_2	b_3	b_4	b_5	b_6	a_1	a_2	a_3	a_4	a_5	a_6
8089.1	1691.0	102.7	1.7811	0.6	-0.6	-1.2	2.5	-1.1	1.7	-2.7	-1.3	-1.6	0.3	0.2	0.1
8063.2	1691.1	102.7	1.7826	0.5	-0.3	-1.3	2.7	-1.0	2.1	-2.9	-1.3	-1.2	0.1	-0.1	-0.6
8075.7	1691.0	102.6	1.7833	0.5	-0.4	-0.6	2.6	-0.3	1.8	-2.0	-1.4	-0.7	-0.2	-0.1	-0.1
8069.2	1691.0	102.6	1.7808	0.6	-0.3	-0.9	3.3	-0.7	1.9	-2.4	-1.2	-0.7	0.1	0.3	0.0
8060.7	1691.6	102.6	1.7791	0.7	-0.4	-0.8	3.1	-0.3	2.6	-2.7	-1.1	-0.7	-0.1	0.2	-0.3

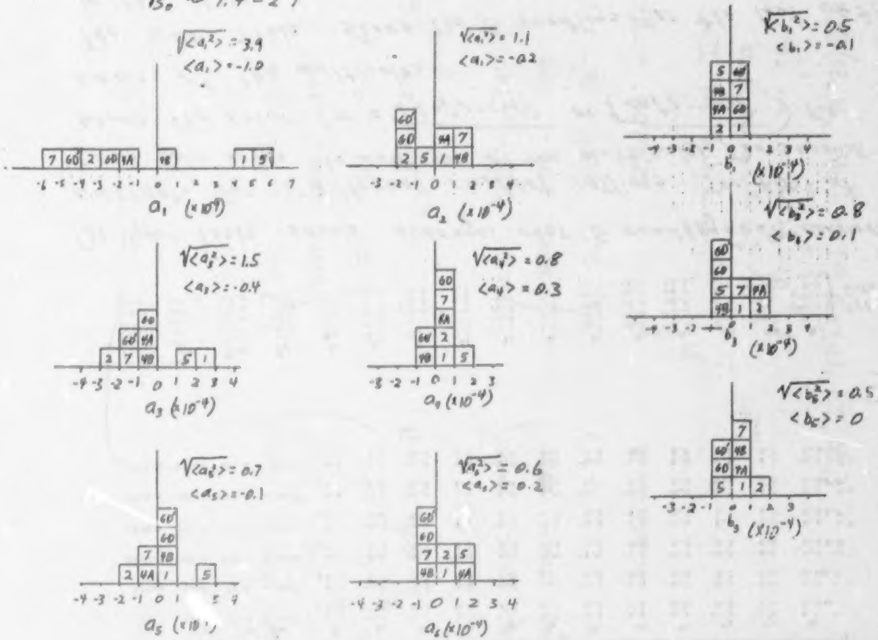
Typical Data

The Upper table shows averages over 5 readings at constant currents for 6 different current settings. The first of each pair shows the averages of the multipoles. The second shows the error ($\sigma \doteq \sqrt{\langle b_i^2\rangle - \langle b_i\rangle^2}$ or $\sqrt{\langle a_i^2\rangle - \langle a_i\rangle^2}$) for each of the multipoles.

The lower table shows the 5 readings for the last entry in the table. (I_{in} tends to decrease slowly as the control circuits in the 12 kA supply heat up.)

Random errors of Forbidden Multipoles

$B_0 \sim 1.4-2\ T$



Random errors

	B_0 (T)	b_1	(×10^{-4}) b_2*	b_3	b_4*	b_5	b_6*	a_1	a_2	a_3	a_4	a_5	a_6
TAC1	1.77	0.1	-0.5	0.4	7.2	0	2.9	4.8	0.4	2.1	0.4	0.7	0.7
TAC2	1.77	-0.9	-0.7	1.2	6.2	1.0	2.4	-3.8	-1.4	-2.4	0.5	-1.2	0.2
TAC4B	1.44	-0.4	0.4	-0.5	-2.4	0.1	-2.4	0	1.3	-0.3	-0.7	0.3	-0.8
TAC4A	1.44	-0.2	0	1.0	2.9	0.1	1.6	-1.7	0	-0.8	0.8	-0.8	1.2
TAC5	1.9-2.0	-0.3	—	-0.4	—	-0.7	—	5.1	-0.6	1.7	1.9	0.8	0.6
TAC7	1.82	0.6	-2.1	0.6	0.7	0.5	1.4	-5.4	1.3	-1.5	0.1	-0.7	-0.2
GD1	1.78	0.5	-0.4	-1.0	2.8	-0.7	2.0	-2.5	-1.2	-0.9	0	0.1	-0.1
GD1'	1.81	0.4	-3.5	-0.5	0.1	-0.3	1.7	-4.6	-1.2	-1.2	-0.8	0	-0.1
TAC9													
TAC10													

* b_2, b_4, b_6 are not random errors, but depend on magnet design + current ratios.

	b_1	b_2*	b_3	b_4*	b_5	b_6*	a_1	a_2	a_3	a_4	a_5	a_6
< >	-0.05	—	0.10		0	—	-1.01	-0.18	-.44	0.34	-0.1	0.19
s	0.54	—	0.81		0.58	—	4.05	1.10	1.16	0.34	0.72	0.63
	0.50		0.71		0.64	—	3.92	1.05	1.51	0.91	0.69	0.62

APPENDIX 12

A Research Proposal

to

DEPARTMENT OF ENERGY

BY

TEXAS A & M RESEARCH FOUNDATION
Box 3578
College Station, TX 77843

ENTITLED

"CONTINUOUS UNITIZED TUNNELING SYSTEM (CUTS)
PROPOSED RESEARCH AND DEVELOPMENT"

RF-84-801

Proposed Duration: 3 years
Amount Requested: $5,297,760
First Year Request: $1,100,000
Requested Starting Date: 11/1/84

Small Business ___ Indian ___ Profit ___ Non-profit _x_ Educational ___
Woman-Owned ___ Socially and Economically Disadvantaged ___

Project Administrator: Dr. Charles H. Samson
Technical Director: Dr. Louis J. Thompson
Civil Engineering Department
Texas Engineering Experiment Station (TEES)
Texas A&M University System
College Station, TX 77843
(409) 845-7115 and (409) 845-3769, respectively

Business Contact: Ms. Susan E. Gandy, Administrator
Contracts and Grants
Texas A & M Research Foundation
Box 3578
College Station, TX 77843
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Date of Submission: August 17, 1984

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ABSTRACT

CONTINUOUS UNITIZED TUNNELING SYSTEM (CUTS)
PROPOSED RESEARCH AND DEVELOPMENT

It is proposed to research, design, build, and demonstrate a new unitized tunneling system that will increase tunneling rates by a substantial factor and at the same time dramatically reduce present-day tunnel costs. These improvements result from a novel approach to the transport of cuttings and liner materials in pipelines, the continuous slip-form extrusion of concrete tunnel linings, and the incorporation of the pipelines into the extruded lining floor. This constitutes the first truly continuous tunneling process.

The purpose of the proposed project is two-fold:

1. Preliminary studies indicate that the economic feasibility of constructing the Superconducting Super Collider (SSC) may well hinge in part upon the development of a tunneling approach having a substantially reduced cost in comparison with the cost of conventional methods. The proposed concept should accomplish such a cost reduction.

2. A critical need exists in both the public and private sectors for a tunneling system that can offer significant improvements from both performance and cost standpoints.

The project will be a cooperative effort between the United States Department of Energy, several compatible industries, and Texas A&M University. A three-year DOE budget of $5,297,760 is proposed with $1,100,000 in FY 85. The industrial partners will contribute in total $1,200,000 and 24 design and engineering personnel.

The project is proposed to begin in November, 1984 and be completed in three years, at the end of which the CUTS technique will have been demonstrated in actual practice.

I. INTRODUCTION

This document is a proposal by a university/industrial consortium for an R&D program on tunnel technology for the Superconducting Super-Collider (SSC). The goal of the program is to design, build, and demonstrate a Continuous Unitized Tunneling System (CUTS) with significant improvements from both performance and cost standpoints. CUTS is a tunneling system in which (1) the tunnel lining is extruded in place from concrete mixed at the tunnel head, (2) the materials for the concrete are transported to the tunnel head in pipes extruded into the lining floor, and (3) the cuttings are removed in a large pipe also extruded into the tunnel floor. In this way all handling of materials in the tunnel is eliminated, and tunneling can proceed for long distances (several miles) between surface penetrations. Both of these features result in an increased tunneling rate and decreased tunnel cost. The CUTS technology is suitable for use in a wide range of soil types (clay, shale, sand, sandstone, limestone) that typify most candidate SSC sites.

The tunnel for the SSC is a major component of the cost of the entire project. In the recently completed Reference Design Study (S8), the tunnel cost is between one-fifth and one-third of the project cost, depending on which magnet design is chosen. Its cost is comparable to the total cost of all superconducting magnets needed for the SSC. This proposal is the only effort proposed to date which aims to try to reduce the tunnel cost by improving the technology used to build it. It has just as much potential cost impact on the SSC construction as the entire magnet R&D program.

We arranged a preview of the proposed CUTS technology, involving representatives from DOE, Bureau of Reclamation, Corps of Engineers, and the tunneling industry. A list of the invited representatives is included as Appendix B. The substantive result was a consensus that the proposed program is well conceived, has potential for significant improvement in tunneling rate and cost, and with ambitious execution may be achieveable in the proposed three-year period for the proposed budget. A number of specific questions were raised and are treated in detail in this proposal.

The proposed program is a three-year effort to be undertaken by a consortium of Texas A&M University and a number of appropriate industrial participants. We request a total DOE funding of $5,297,760 of which $1,100,000 is in the first year (FY 85). We are requesting industrial funding of $1,200,000 plus professional staff support equivalent to 24 personnel. About half of the industrial contributions have been committed to date, contingent on DOE approval.

In order to meet the three-year time scale needed for relevance to the SSC construction schedule, Texas A&M University System intends to commit its own resources through the fall 1984 semester for the planning, design, and initial tests of CUTS technologies. Thus we are beginning the program immediately, and must obtain FY 85 funding from DOE at the earliest possible date.

II. NEED FOR THE PROPOSED PROJECT

Underground tunnels serve many useful purposes. Man has been building them since the beginning of time. One of the most ancient uses for tunnels was the gravity transport of water to fortified cities, and from the mountain foothills to deserts where agriculture began. There is an ancient water tunnel into Jerusalem, and in Iran alone there are over 15,000 miles of hand-dug water tunnels called "qanats" that carry water from the mountain streams to the desert playas. The city of Tehran still gets its water from qanats. Modern water tunnels are a major part of the California water system that transports water from Northern California and Arizona to Southern California. Many long, high-pressure water tunnels are used in modern-day hydroelectric power projects. In Guatemala there is a 15-foot diameter water tunnel over 16 miles long that carries water at pressures in excess of 150 psi. China is now building long water tunnels with diameters in excess of 30 feet. These water tunnels may be concrete lined or in sound rock unlined. Depending on rock competence, the linings may be reinforced or unreinforced.

With the industrial revolution came railroad tunnels built through mountains and under rivers. Now there are similar tunnels for highway vehicles. The most modern vehicular tunnel is the 37-mile undersea tunnel that connects the two northern islands of Japan.

As modern cities become larger and increasingly congested, tunnels are needed for subway trains to transport people faster and more easily. Washington, D.C. and Atlanta, Georgia are now completing their subway system. The growing populations of older cities also overload old utility systems until they break down. In one intersection in New York City, there are 254 pipelines. Old brick sewers degrade, leak, and collapse. Old metal lines corrode and leak. It is said that older cities are starting to drown in their own wastes as one utility contaminates another. Cities are fast realizing that their utilities must be collected into tunnels. In recent years some political leaders - and others - have advocated a national effort to rebuild the infrastructure. Utility lines that could be collected into a tunnel below the street might include water lines, sanitary sewers, storm sewers, electric power lines, oil lines, gas lines, slurry-coal lines, telephone trunk lines, steam lines, cold-water lines, hot-water lines, television cables, liquid-chemical lines, and pneumatic lines to transport particulates. Many of the large cities have huge projects where interceptor sewers are being built as much as 100 feet below the streets to collect waste water that cannot wait for the rebuilding of the infrastructure. Chicago, Baltimore, Austin, and Mexico City are some of these cities. The U.S. Corps of Engineers is planning for San Antonio a new storm sewer under the "river walk."

Many cities have built pedestrian tunnels to connect buildings, underground railroad stations, and subway stations. Montreal, Kansas City, and Houston have extensive tunnel walkways. Often stores and theaters are built underground to serve the traffic.

Underground mining, military tunneling, sapping, and protective structures depend on the art of tunneling. The ICBM Deep Basing Egress System has been in development since 1982 (Program Manager: Bechtel National, Inc.). In the event of a war, tunnels could provide a significant refuge.

Tunneling and tunnel research are major Russian efforts. Sweden has been going underground since the mid 1800s. Transportation facilities, fuel storage, food storage, churches, factories, water-treatment plants, and even military aircraft hangers are found underground.

A new tunneling need has recently arisen as physicists require even bigger particle accelerators to study the essence of matter and energy. The scientific equipment is buried in the earth, and the earth must be tunneled to protect nearby life from radiation in event the beam of accelerated particles is accidently lost. Large new accelerator tunnels are now being built in California, Switzerland, and Germany. With the proposed Superconducting Super Collider, the United States will construct a 100-mile (or longer) circular tunnel ten feet in diameter. With the application of existing tunnel technology, the cost of the tunnel would probably equal or exceed the cost of the accelerator that is accommodated. The proposed project would develop and demonstrate a new tunneling system that could dramatically lower the cost of tunneling and speed the tunneling process.

In a general way, then, the proposed research and development program is pointed toward meeting a two-fold need:

1. A much-improved approach to meeting the tunneling requirements of the Superconducting Super Collider (SSC).

2. A critical need in both the public and private sectors for a tunneling system that can offer significant improvements from both performance and cost standpoints.

III. TECHNICAL BACKGROUND

The cost of tunneling usually decreases as the speed of tunneling increases. For a given rate of power use, the rate of tunneling increases when the six major operations of tunnel construction progress continuously and simultaneously. These major tunnel operations are as follows:

1. Ground control. It is necessary to prevent closure or collapse of the bore, inflow of water, and settlement of the ground surface. Often in soft soils a tubular steel shield is thrust through the ground to prevent collapse of the soil above. The rate the soil moves into the tube can be controlled by shutters or by slurry pressure. Internal air pressure can be used to control the inflow of water or the soil can be grouted to decrease its permeability. In harder soil and rock, none of these measures may be required. Generally, the softer the soil the more expensive is this operation.

2. Excavation of the soil or rock at the head of the tunnel. Very soft soil may flow into the shield, but harder soil and rock must be dug, ripped, cut, bored, or finally - if sufficiently hard - drilled and blasted. The result of this operation is rock or soil particles, i.e., muck. The cost of excavation increases with rock hardness. Boring rates increase as the thrust on the cutter bits increases and as the rate of revolution of the cutter head increases. High specific energy is required to break the rock into small particles; therefore, large-particle excavation is more efficient than small-particle excavation.

3. Collection and transport of the muck back through the tunnel and up a shaft for disposal. The muck can be picked up with shovels, backhoes, conveyer belts, fluids, or air. The transport can be by railcar or

pipeline. Generally, the fewer times the muck has to be handled, the faster is the operation. The speed of tunneling is primarily determined by the rate the muck can be removed and transported out of the tunnel. Pneumatic pipeline transport is the fastest and the most expensive. Slurry pipeline transport is about ten times cheaper than pneumatic pipeline transport but is much slower. Slurry transport in turn is much faster than rail transport. In both hydraulic and pneumatic transport of particles, the fluid velocity required to suspend and move particles decreases as the size of the particles decreases. Muck transport by slurry pipeline is being used in soft-ground tunneling in both Europe and Japan. The main disadvantage is that the pipeline can be telescoped only about 30 feet. When this limit is reached, the pipes must be disconnected, fluids are lost, and new pipe must be brought forward and reconnected before boring can recommence.

4. Transport of lining and support materials to tunnel head. Usually rail cars are used to transport ribs, lagging, steel reinforcing bars, wet concrete, or precast concrete segments. Sometimes the wet concrete is pumped from a transfer station into the forms for the final lining. Ordinarily wet concrete will not be pumped farther than about 1,000 feet. Shutdown and cleaning of the wet concrete pipeline are a major problem.

5. Construction of the permanent impervious lining. Often temporary tunnel support composed of steel ribs and lagging is erected initially. Later, forms are erected and concrete is pumped behind the forms to construct a finished impervious lining. Another method uses precast concrete segments that are transported by rail to the tunnel head and rotated into place with an erection machine. Grout is pumped behind

the precast segments (and also in cast-in-place lining) to put the lining in compression and to fill voids behind the precast segments. In new developments in Germany and Japan, the temporary supports are eliminated by using a long shield. After boring about 30 feet, forms are brought up and set inside the shield. Fiber-reinforced concrete is brought to the tunnel head and pumped into the forms. As the concrete sets, the machine bores. When the fast-set concrete is sufficiently stiff, the forms are slipped forward. In both the German and Japanese operations, all muck and concrete are moved by rail. Often in rock with longer stand-up times, rock bolts are installed by drilling and grouting of steel rods into the roof of the tunnel. Also, sprayed-on shotcrete or gunite is frequently used to line tunnels through rock. Sometimes in hard, competent rock, no linings are needed.

6. Control and sensing system with feedback loops to direct the machine and to regulate electric motors and solenoid valves. Most boring machines are controlled manually and directed by a laser beam. Feedback loops are usually manual operations with radio and telephone.

Tunneling operations individually have been or can be made very efficient. However, in such a confined space, the six major operations often interfere with one another and the process becomes messy, dangerous, and chaotic. One of the major obstacles to continuous operations is the rail system. Two-way traffic on a single line and the switching and handling required at the tunnel head and shaft slow all operations. Bringing rail up and extending the rail line also slow all operations. Many of these difficulties can be eliminated by moving all materials in and out of the tunnel by pipeline. The obstacles to this method are that the pipelines must be regularly extended, and wet concrete for tunnel lining and support cannot be pumped very far.

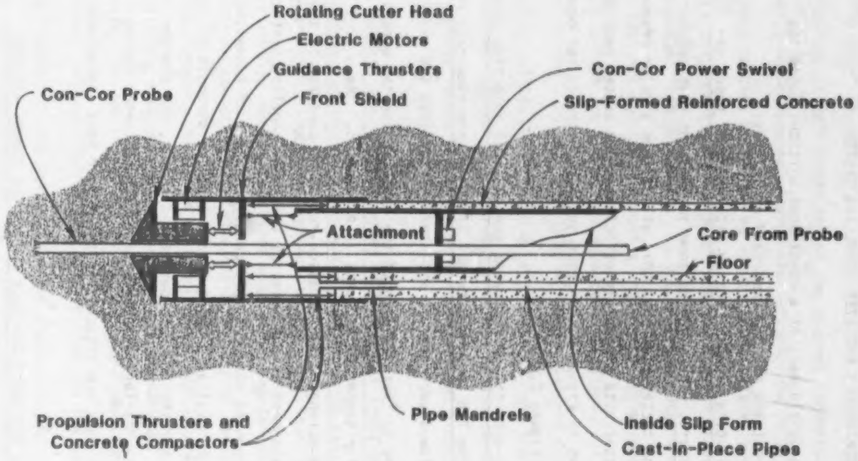
IV. CONTINUOUS UNITIZED TUNNELING SYSTEM

The concept for the development of a continuous unitized tunneling system is shown in Figure 1 and may be summarized as follows:

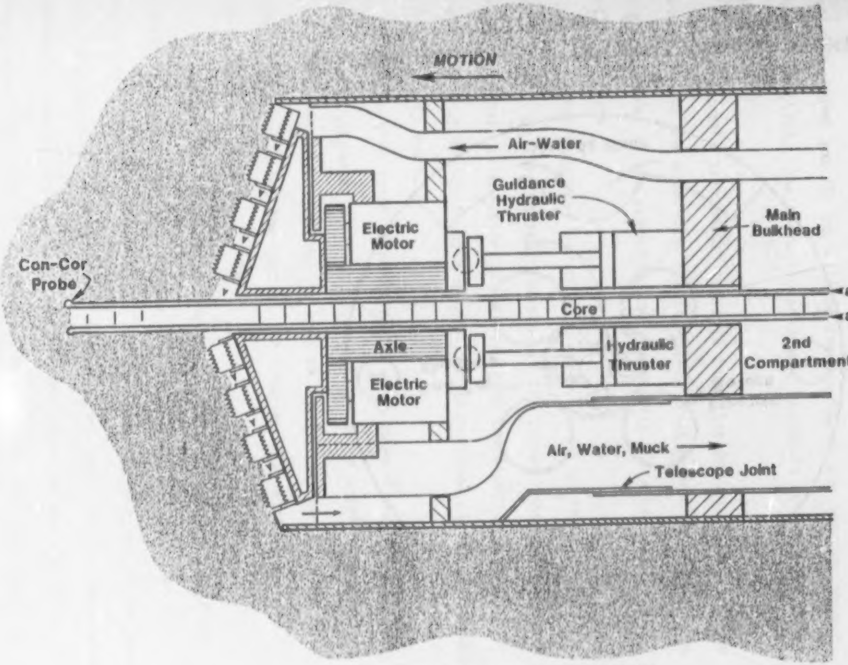
1. Bore the tunnel using a tunnel boring machine (TBM) based on present-day state-of-the-art. There may be some improvement that can be made in the design of the cutter bits, but this will not be a major research effort since present cutter bits are fairly efficient. The cutter head and its compartment are shown in Figure 2. A cross section of the cutter head compartment is shown in Figure 3.

2. Develop a rapid-set, fiber-reinforced concrete for injection into slip forms attached to the TBM to form a tunnel lining at the same rate the tunnel is bored. This low-slump concrete will be injected into the slip forms under high pressure so that yielding of the earth around the bore is minimized and the need for temporary supports is eliminated. The development of the early-strength/high-abrasion-resistant concrete is the key element for the development of a continuous unitized tunneling system that can travel fast enough to change significantly the cost of tunneling. Several concrete mixes are available which attain adequate strength in less than one hour. The quicker the concrete develops strength, the shorter the slip forms can be and the smaller the drag will be on the tunnel boring machine. The slip forms that are attached to the cutter head compartment are shown in Figure 1.

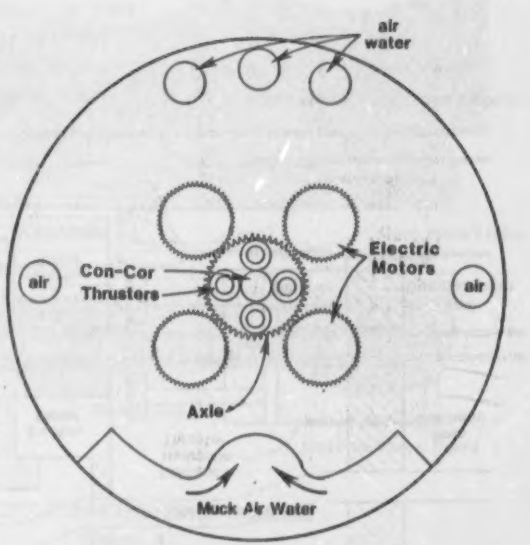
3. Use pipelines to transport the muck out of the tunnel and the concrete materials to the head of the tunnel in order to minimize handling. The vehicle to transport the muck will be air or water or a combination of air and water as needed to minimize the power required for material


Rotating Cutter Head
Electric Motors
Guidance Thrusters
Front Shield
Con-Cor Probe
Con-Cor Power Swivel
Slip-Formed Reinforced Concrete
Attachment
Core From Probe
Floor
Propulsion Thrusters and Concrete Compactors
Pipe Mandrels
Inside Slip Form
Cast-in-Place Pipes

UNITIZED TUNNEL SYSTEM SCHEME
Figure 1.


MOTION
Air-Water
Guidance Hydraulic Thruster
Main Bulkhead
Electric Motor
Con-Cor Probe
air
air
Core
Axle
Hydraulic Thruster
2nd Compartment
Electric Motor
Air, Water, Muck
Telescope Joint

CUTTER HEAD COMPARTMENT
Figure 2.



air
water
Electric
Motors
air
Con-Cor
Thrusters
air
Axle
Muck Air Water

SECTION THROUGH CUTTER HEAD COMPARTMENT
Figure 3.

transport. In special situations, clay or foam may be added to the air or water. The cement and fly ash will be transported in air only to prevent premature hydration. The hydraulic-pneumatic transport scheme is shown in Figure 4.

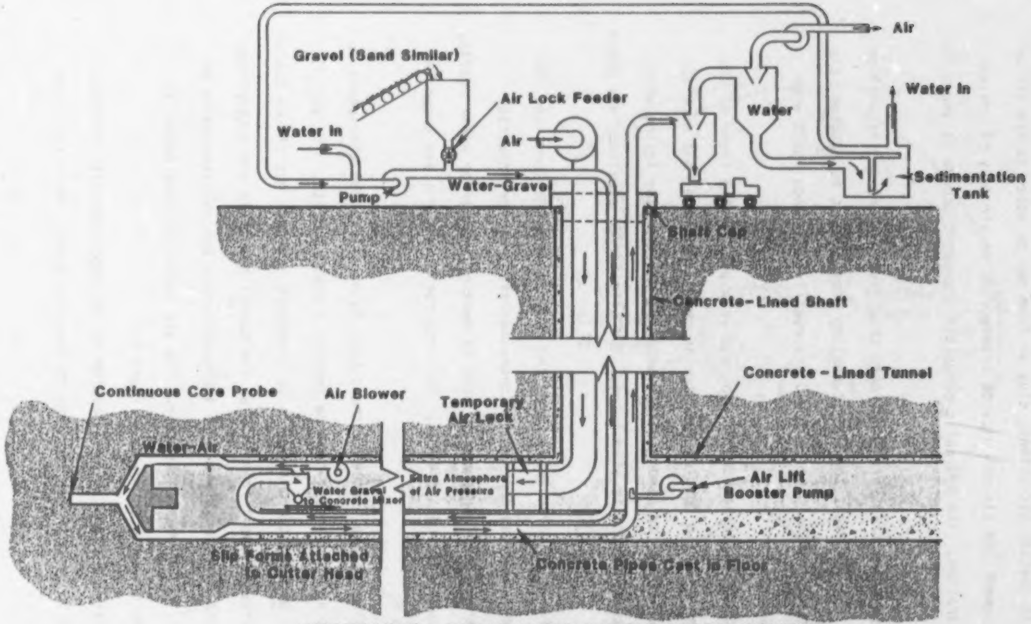
In all pipeline transports, not more than five percent solids will be transported. In the event that the tunneling process must be stopped, the solids are stored in the pipelines and are readily entrained again when operation resumes.

4. Cast the pipelines out of concrete as a part of the floor of the tunnel lining. By slip forming the pipe at the tunnel head, all muck and concrete materials circulation is kept separate and pipeline laying with attendant loss of fluids is eliminated. The slip-formed pipelines are shown in Figures 4, 5, and 6.

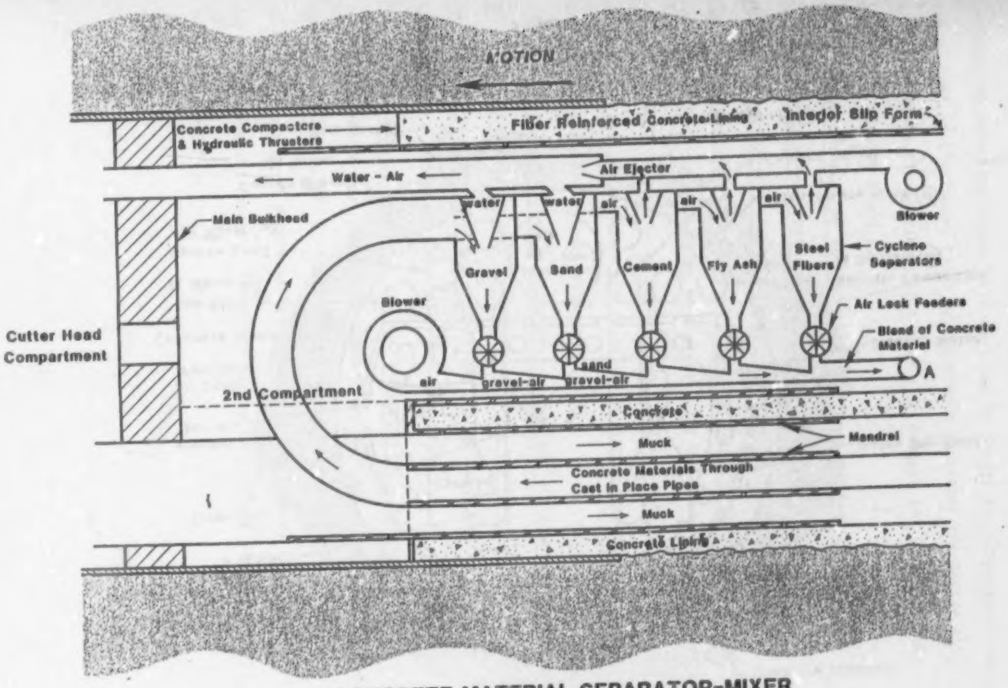
5. Design slip forms to minimize the drag between the forms and the freshly placed compacted concrete. Controlled air or water injection through sintered-metal forms may be used to develop any air or water bearing between the concrete and the forms. The interior slip forms are shown in Figures 1 and 5.

6. Pressurize the inside of the tunnel no more than one atmosphere to provide air support overhead for the freshly placed concrete. The air pressure will provide the air source to transport the muck out of the tunnel and to help prevent water intrusion at the tunnel head. In the cutter-head compartment the air pressure can be increased above the one atmosphere to prevent water intrusion if necessary. The air locks and fans needed to pressurize the tunnel are shown in Figure 4.

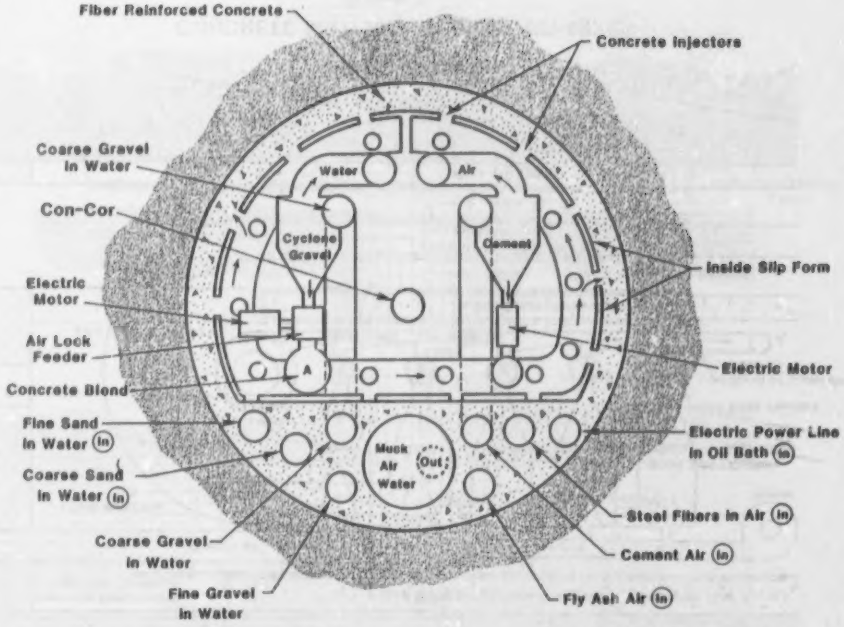
7. Propel the tunnel boring machine by the same hydraulic thrusters that are used to compact the concrete in the slip forms. Auxiliary side


Gravel (Sand Similar)
Air Lock Feeder
Air
Water In
Water
Air
Water In
Pump
Water-Gravel
Sedimentation Tank
Shaft Cap
Concrete-Lined Shaft
Concrete - Lined Tunnel
Continuous Core Probe
Air Blower
Temporary Air Lock
Water-Air
Extra Atmosphere of Air Pressure
Water Gravel to Concrete Mixer
Air Lift Booster Pump
Slip Forms Attached to Cutter Head
Concrete Pipes Cast in Floor

HYDRAULIC - PNEUMATIC CIRCULATION SCHEME
FOR CONTINUOUS MUCK AND CONCRETE MATERIALS TRANSPORT
Figure 4.


MOTION
Fiber Reinforced Concrete Lining
Integral Slip Form
Concrete Compacters & Hydraulic Thrusters
Water - Air
Air Ejector
Blower
water
water
air
air
air
Main Bulkhead
Cyclone Separators
Gravel
Sand
Cement
Fly Ash
Steel Fibers
Air Lock Feeders
Blower
Blend of Concrete Material
Cutter Head Compartment
sand
air
gravel-air
gravel-air
A
2nd Compartment
Concrete
Mandrel
Muck
Concrete Materials Through Cast in Place Pipes
Muck
Concrete Lining

CONCRETE MATERIAL SEPARATOR-MIXER
Figure 5.


Fiber Reinforced Concrete
Concrete Injectors
Coarse Gravel In Water
Water
Air
Con-Cor
Cyclone Gravel
Cement
Inside Slip Form
Electric Motor
Air Lock Feeder
Electric Motor
Concrete Blend
A
Fine Sand In Water (In)
Electric Power Line In Oil Bath (In)
Muck Air Water
Out
Coarse Sand In Water (In)
Steel Fibers In Air (In)
Coarse Gravel In Water
Cement Air (In)
Fine Gravel In Water
Fly Ash Air (In)

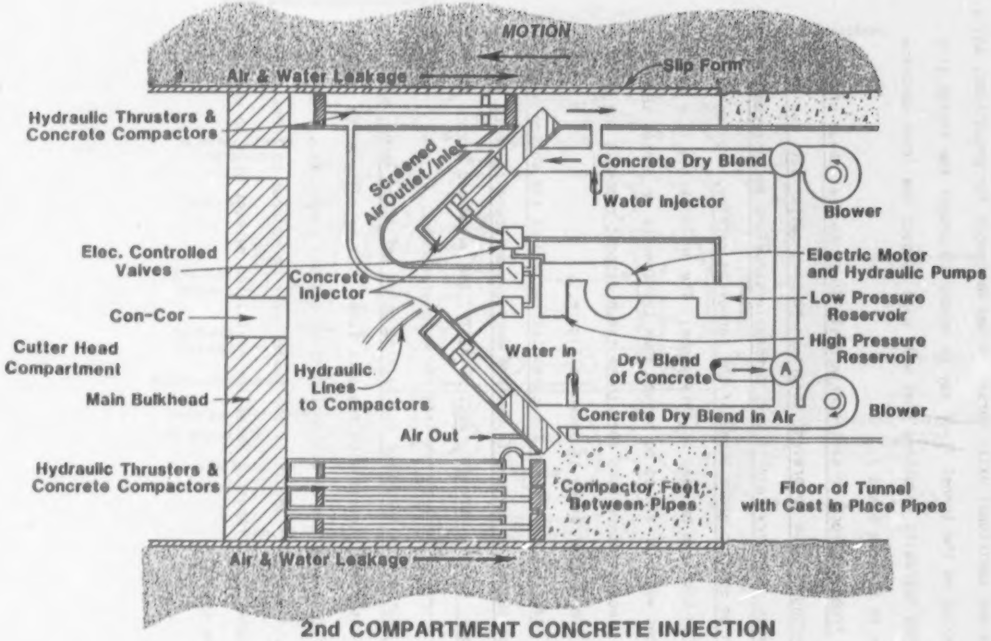
SECTION THROUGH CONCRETE MIXING COMPARTMENT
Figure 6.

thrusters and additional axial thrusters may be needed for propulsion, and a crawler track on the tunnel floor may be needed to propel the inside slip forms. The hydraulic thrusters that will also compact the fresh concrete are shown in Figures 5 and 7.

8. Probe the rock or soil continuously 30 to 40 feet ahead of the tunnel boring machine to prevent surprises so that cutter bits can be changed when necessary, and if very permeable sands are encountered the probe can be used to grout ahead of the tunneling machine. A patented device called "Con-Cor" can be used as this probe. The drill string is a dual pipe that allows water or air to be pumped down the annulus to propel the six-inch piece of continuous core to be taken without removing the drill string. The Con-Cor probe is shown in Figure 1.

9. Analyze continuously the cores taken ahead of the boring machine by the use of automated devices to measure density, moisture content, length of intact core, tensile strength, etc. Finally, the automated device will store the cores or inject them into the muck stream.

10. Automatically direct the machine using deflected laser beams. Electronic sensing devices with feedback loops will be designed to control hydraulic thrusters for directional control and all pumps, fans, and motors so that the number of people in the tunnel will be reduced to those required for maintenance and repair. Satellite navigation methods will be used to locate the shafts.


MOTION
Air & Water Leakage
Slip Form
Hydraulic Thrusters & Concrete Compactors
Screened Air Outlet/Inlet
Concrete Dry Blend
Water Injector
Blower
Elec. Controlled Valves
Concrete Injector
Electric Motor and Hydraulic Pumps
Low Pressure Reservoir
Con-Cor
Cutter Head Compartment
Main Bulkhead
Hydraulic Lines to Compactors
Water In
Dry Blend of Concrete
A
High Pressure Reservoir
Blower
Concrete Dry Blend in Air
Air Out
Hydraulic Thrusters & Concrete Compactors
Compactor Feet Between Pipes
Floor of Tunnel with Cast in Place Pipes
Air & Water Leakage

2nd COMPARTMENT CONCRETE INJECTION
Figure 7.

V. COST COMPARISON OF PROPOSED AND CONVENTIONAL TUNNELING APPROACHES

It is of course difficult to project the cost of a technology before it is developed. At the same time, the potential for cost savings is of central concern in evaluating the CUTS technology. We have estimated the cost of CUTS tunneling by treating costs of equipment, labor, maintenance and repair, and energy for each of the major activities. Costs are based on a ten-foot inner diameter and a flat floor three feet above the tunnel bottoms. A CUTS tunneling rate of 60 feet per hour is assumed. Note that this rate is well within the performance of all systems, calculated in previous sections, and is attainable in a variety of soil types (clay, sand, shale, sandstone, soft limestone).

The major cost categories are compared in Table 1 with costs for present-day tunneling based on analysis of recent contract experience. All costs are expressed as percentages of the total cost using conventional tunnel technology. The CUTS technology is projected to be about one-third the cost of conventional tunneling. The dramatic difference is due to a number of specific advantages, most of which occur because of the elimination of materials handling in the tunnel. These differences are discussed as follows:

1. Excavation:

The continuous unitized tunneling system (CUTS) excavation costs should be about the same as the conventional tunneling-system (CTS) excavation costs when both machines are boring at the same rate. However, it is expected that CUTS will bore nearly continuously. In contrast, CTS often only bores one-third of the time.

2. Muck Transportation:

The muck transportation cost of CUTS should be roughly one-third that of CTS because no train, flat cars, muck cars, and locomotives must be bought. No hand labor is required to extend the tracks systems, switch the cars, operate the loader, drive the train, switch the cars at the shaft, operate the elevator, etc. The muck transport costs for CUTS depends on the cost of the pumps and the power to operate them. It is doubtful that this cost will exceed 6 percent of the total CTS costs, in contrast to the train muck system cost which is about 20% of the total CTS cost.

3. Temporary Supports

With CTS temporary supports may cost as much as 13 percent of the total cost. The expendable steel ribs and wooden lagging must support the ground until the lining operation can begin. CUTS does not require any temporary supports because the final lining is extruded as the tunnel is bored. Most of high cost of ribs and lagging is in erection labor.

4. Reinforcing Steel

With CTS reinforcing bars for the tunnel lining may cost as much as 31% of the finished total cost and like the temporary supports most of this cost is in erection labor. The steel fiber reinforcing of the extruded concrete lining for CUTS carries no labor costs. Material cost for the steel fibers should be about 3 percent of the total cost of CTS.

5. Formwork:

The formwork for cost in place concrete tunnel linings is an ingeneous articulated system that allows one-half of the forms to pass through the other half. The system is patented and expensive to build and operate. Often the cost of the forming operation for CTS is 10% of the total cost. The slip forms for CUTS will be much simpler and require no labor, except for maintenance. They should not cost any more than 2 percent of the total cost of CTS.

6. Concrete Lining:

In CTS, concrete is batched at the surface and transported to the forms in revolving drums on train cars. It is then pumped into the forms. Often this operation will cost as much as 11% of the total cost of CTS. For CUTS the batch plant at the tunnel head should cost a little more than the cost of a surface plant. The power required for hydraulic transport of materials should cost somewhat less than the power for rail transport. The labor costs to pump the concrete into the continuously operating slip forms should be much less than the labor cost for the discontinuous pumping of concrete into the conventional forms. More concrete materials may be required for CUTS than for CTS because the pipes will be cast in the floor. It is estimated that the concrete costs for CUTS will be about 9% of the total cost of CTS.

7. Lining Backfill

Usually the concrete shrinks in CTS and the void must be filled by pumping gravel or crushed rock behind the lining. This can cost as much as 2% of the total cost. Because in CUTS the very dry fiber reinforced concrete will be compacted into place, there should be no shrinkage and no backfill should be required.

Other costs such as power distribution, communications, directional control, and ventilation should be roughly the same for both systems with the exception that air pipe will not have to be extended in the CUTS.

Table 1

Comparison of the relative costs of a conventional tunneling system (CTS) and a continuous unitized tunneling system (CUTS)

Cost Items		Equipment	Materials	Transport Power	Labor	Total
1 Excavation	CTS CUTS	3% 5%		2% 2%	2% 1%	7% 8%
2 Muck Transport	CTS CUTS	10% 3.5%		1% 1%	9% 1.5%	20% 6%
3 Temporary Supports	CTS CUTS	1%	4% None	1% Required	7%	13% 0%
4 Reinforcing Steel	CTS CUTS		5% 2.5%	1% 0.5%	25%	31% 3%
5 Formwork for Lining	CTS CUTS	2% 2%		1%	7%	10% 2%
6 Concrete Lining	CTS CUTS	1% 2%	4% 5%	1% 1%	5% 1%	11% 9%
7 Lining Backfill	CTS CUTS		1% None	0.5% Required	0.5%	2%
8 Power Distribution	CTS CUTS	2% 2%			1% 1%	3% 3%
9 Communication and Feedback	CTS CUTS	0.5% 0.5%			0.5% 0.5%	1% 1%
10 Directional Control	CTS CUTS	0.5% 0.5%			0.5% 0.5%	0.2% 0.2%
11 Air Lines and Ventilation	CTS CUTS	0.5% 0.5%		0.3% 0.3%	0.2% 0.2%	1% 1%
Totals	CTS CUTS	20.5% 14.0%	14% 7.5%	7.8% 4.8%	57.7% 5.7%	100% 32%

VI. RESEARCH AND DEVELOPMENT APPROACH

To be successful, the proposed work must make very effective use of the best university and industry resources that can be brought to bear in a well-integrated, cooperative fashion. The effort must also recognize its two-fold purpose:

1. To provide a much-improved approach to meeting the severe requirements of the Superconducting Super Collider (SSC).

2. To provide a "systems approach" to tunneling that can make it significantly more attractive in meeting the many, varied needs of the public and private sectors.

The project is being organized as a university/industrial consortium. The roles of the participating institutions ar summarized as follows:

Texas A&M University

1. Program management
2. Budget responsibility to DOE
3. Design coordination
4. Provision of site/space for tunnel tests
5. Involvement of appropriate faculty and students in all tasks of project

Major Industrial Participant

1. Design responsibility/credit for significant task within project
2. Design/construction of equipment for task, subject to coordination at TAMU
3. Annual contribution of $50,000, plus 4 FTE design/engineering personnel, for the 3 year project duration.
4. DOE subcontrct for technician/shop labor, materials, equipment construbtion appropriate to task.
5. Right without fee to use of all technology developed during the program.
6. Protection of patent rights on technology patented by participant prior to participation in CUTS.

Minor Industrial Participant

1. Design/construction of specific components/services relevant to expertise
2. Annual contribution of 1/2 FTE design/engineering personnel.
3. Provision of appropriate standard equipment of internal manufacture or services as appropriate, to be charged to DOE contract at cost.

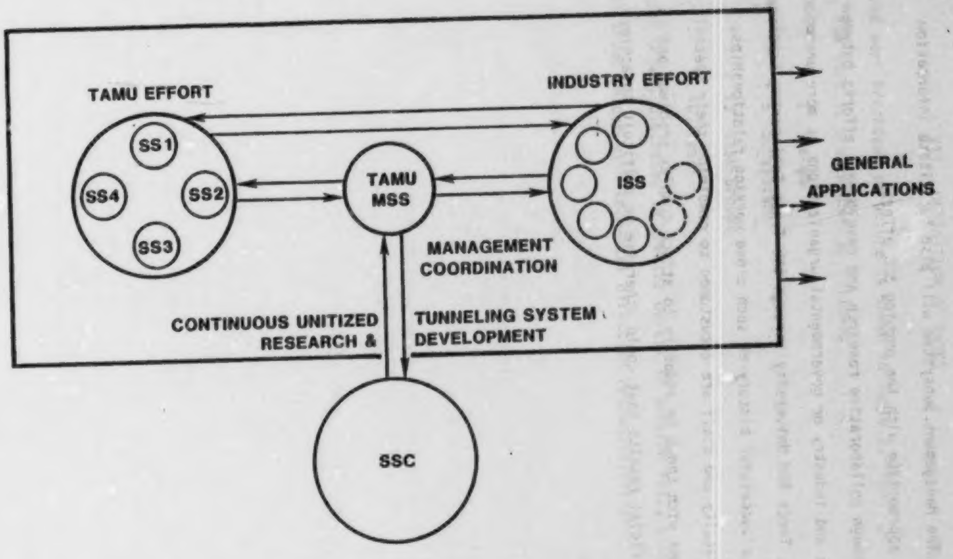
Figure 8 illustrates the elements of the planned interactions. The tunneling system is conceived as comprising four subsystems:

1. Tunneling Boring Subsystem (SS1)
2. Tunneling Lining Subsystem (SS2)
3. Slip-Forming Subsystem (SS3)
4. Control and Detection Subsystems (SS4)

Each of the above subsystems includes an array of tasks that will be described later.

The Industry Subsystem (ISS) includes various "major participants" and "minor participants" from industry, where the terms "major" and "minor" refer to different degrees of participation in the research and development effort through the projected three-year life of the program. It is expected that industry participants will contribute substantially to the ongoing tasks encompassed by the four subsystems identified above.

Because a "systems approach" is being used to incorporate all aspects of the tunneling problem, and because of the problem complexity that requires the identification of many separate but closely related tasks, of critical importance is the effective meshing of the task efforts and the input of both university staff and industry participants. This will be accomplished through the Management Subsystem (MSS), which will provide for management coordination, technical coordination, and program planning and


TAMU EFFORT
SS1
SS2
SS3
SS4
TAMU MSS
INDUSTRY EFFORT
ISS
GENERAL APPLICATIONS
MANAGEMENT COORDINATION
CONTINUOUS UNITIZED RESEARCH &
TUNNELING SYSTEM DEVELOPMENT
SSC

RESEARCH AND DEVELOPMENT INTERACTIONS
Figure 8.

scheduling. The Management Subsystem will also facilitate information exchange as appropriate with the ongoing SSC effort.

Even though collaborative research and development efforts between universities and industry or governmental organizations is more uncommon than common, Texas A&M University through the Texas Engineering Experiment Station has a successful history of such close working relationships. University faculty and staff are accustomed to combining their special qualifications with those in industry to attack complex problems and to produce beneficial results that would otherwise be difficult to achieve.

VII. DEFINITION OF TASKS

The coded work breakdown structure is shown in Table 2. For venience, the work is broken down as follows:

1 System
5 Subsystems
13 Task Groups
40 Tasks

Each Task Group, discussed in greater detail in Section VIII, will be der a Task Group Leader with technical direction responsibilities.

TABLE 2

TASK DEFINITIONS

0. Management & Coordination Subsystem

	Task Group	Task No.	Task Designation
0.1.	Management & Coordination	0.1.1.	Program Management & Coordination
		0.1.2.	Program Technical Coordination
		0.1.3.	Program Planning & Scheduling

1. Tunneling Boring Subsystem

	Task Group	Task No.	Task Designation
1.1.	Cutter Head Assembly	1.1.1.	Cutter Bits
		1.1.2.	Cutter Head
		1.1.3.	Scour System for Muck Disposal
1.2.	Power Transmission	1.2.1.	Hydraulic Thrusters
		1.2.2.	Torque Motor & Hydraulic Motor
		1.2.3.	Electric Power Transmission
		1.2.4.	Hydraulic Pumps & Directional Control System

2. Tunneling Lining Subsystem

	Task Group	Task No.	Task Designation
2.1.	Concrete Materials Handling & Transport	2.1.1.	System of Surface Tanks, Silos, & Bunkers with Fluidizing Beds
		2.1.2.	Surface Blowers & Injectors to Propel Cement & Fly Ash
		2.1.3.	Surface Pumps & Injectors to Propel Sand, Gravel, & Wire Fibers
		2.1.4.	System for Material Pickup at Surface
		2.1.5.	Piping for Pressure, Abrasion Resistance, & Flow Rate (Conc. Mtls., Air/Water)
		2.1.6.	Air-Lock Feeders & Metering Devices
2.2.	Concrete Materials Separation, Mixing & Injection	2.2.1.	Materials Separation & Metering System
		2.2.2.	Concrete Materials Mixing & Conveyance System
		2.2.3.	System for Concrete Injection & Compaction Into Slip Forms
		2.2.4.	System for Grout Injection Through Probe
2.3.	Concrete Mix	2.3.1.	Concrete Mix

TABLE 2 (Cont'd.)

TASK DEFINITIONS

Task Group	Task No.	Task Designation
2.4. Muck Handling & Transport	2.4.1.	Piping for Pressure, Abrasion Resistance, & Flow Rate (Muck, Air/Water)
	2.4.2.	Booster Pumps & Blowers
	2.4.3.	System for Surface Muck Separation
	2.4.4.	Muck-Pickup System
	2.4.5.	Muck-Disposal System
2.5. Surface Blowers for Pressurization & Ventilation	2.5.1.	Surface Blowers to Pressurize & Ventilate Tunnel

3. Slip-Forming Subsystem

Task Group	Task No.	Task Designation
3.1. Structural Analysis	3.1.1.	Transient Structural Analysis Procedure for Lining & Pipes
3.2. Slip Forms	3.2.1.	Outside Shield, Structural Components, & Pressure Bulkhead
	3.2.2.	Concrete Slip Forms That Minimize Drag
	3.2.3.	Slip-Form Propulsion System

4. Control & Detection Subsystem

Task Group	Task No.	Task Designation
4.1. Direction Control	4.1.1.	System for Direction by Laser Deflection & Computer Procedure to Determine Path Deviation
4.2. Flow-Rate Detection & Control	4.2.1.	Flow-Rate Detection System for All Components
	4.2.2.	Penetration-Rate Detection System
	4.2.3.	Feedback System for Thrust & Torque Control
	4.2.4.	Feedback System for Pump & Blower Control
4.3. Probe	4.3.1.	Probe to Take Cores Continuously
	4.3.2.	Automated Core Analyzer
	4.3.3.	Pore-Pressure Detection System in Probe
	4.3.4.	Possible Geophysical Equipment to be Attached to Probe

VIII. DISCUSSION OF TASKS

GENERAL COMMENT

The work to be accomplished during the first year of the program will be discussed by "Task Group" during the remainder of this section. In each case Objectives will be stated, relevant Background will be provided, the Planned Approach to Meeting Objectives will be described, and Special Equipment Needs, if any, will be identified.

ROUP 0.1. - MANAGEMENT

Objectives - The objectives of the Management Task Group are
1. To provide overall management coordination and direction to the
rch and development program.

2. To provide technical coordination to the various tasks being
taken.

3. To provide the planning and scheduling needed to assure the
ctive and timely completion of all tasks.

Background - The preliminary technical study that has been made
cates the various elements of the concept are feasible, but that a
arch and development effort is needed in order

1. To design the elements such that they will contribute to the
ctioning of the total system in the most effective way from the stand-
nt of system performance.

2. To involve a mix of University capabilities and appropriate
ustry capabilities to accomplish the most effective design and con-
uction of the system.

3. To organize the research and development effort to be compatible
h the ongoing research and development effort of the Superconducting
er Collider.

The above needs involve complex interactions that must be recognized
planning and managing the program.

Planned Approach to Meeting Objectives - The breakdown of the total system effort into subsystems, task groups, and tasks is shown in Table 2. Persons involved in each Task Group effort are identified in Section XI.

The Program Manager will have the responsibility for the overall management, coordination, and planning activities, and will perform the functions required to integrate the various activities so as to meet program milestones.

The Program Technical Coordinator will work with the Program Manager and with the various Task Group Directors to assure that technical progress is being made in a way that is both timely and consistent with overall system technical objectives.

The Program and Scheduling Coordinator will assist the Program Manager by maintaining updated scheduling and progress charts for all aspects of the ongoing program. This coordinator will also have the responsibility for developing appropriate planning and scheduling approaches for possible use in the application of the Continuous Unitized Tunneling System.

Section IX discusses the scheduling of the various research and development activities.

ASK GROUP 1.1 - CUTTER ASSEMBLY
ASK GROUP 1.2 - POWER TRANSMISSION

Objective - To design a hybrid tunnel boring machine to operate under a ide range of conditions. The tunnel boring system must be capable of enetration rates consistent with the rest of the system. The peak oring-rate goal is two feet per minute for an 11-foot bore in clay, shale r soft sandstone. The muck must be delivered to the head of the disposal ystem with a size distribution suitable for slurry transport. In order to inimize cutter changes, the cutting system must be capable of operating in a variety of different lithologies. A major consideration must be maintenance. In particular, the system should allow cutter replacement quickly and safely. Finally, the system must be capable of boring under mixed-face conditions and under a variety of groundwater conditions. The boring machine should accommodate the use of disk bits, mill-toothed bits, and drag bits with provision for water-jet cutting assistance.

Background - An essential part of the unitized tunneling system is the design of the rock-cutting and muck-delivery systems. These systems will consist of the rock-cutting bits, the head in which they are mounted, and the delivery system of the muck to the head of the disposal system. The basic concepts of tunnel boring machines have been used for over 100 years and the cutting mechanisms have been studied and refined during that period (R3). Tunneling machines can be roughly divided into two major types: (1) tubular shields that are jacked forward through soft soil to provide a protected working space for soil inflow control, excavation equipment, muck-disposal units, and lining-erection machinery; and (2) tunnel boring machines (TBM) that are rotating cutter heads with bits on them to break up hard rock as they are jacked forward.

These machines have many variations and subtypes. A mechanized shield has an excavator inside the shield which may or may not rotate. If it does rotate, the bits do not cut the soil outside the shield. A tunnel boring machine with a complete shield that is smaller than the diameter of the bored tunnel is called a shielded tunneling machine (S4).

Drag bits are often used on the cutter heads of soft-ground boring machines, and disk or toothed cutters are often used on hard-rock boring machines. Sometimes the cutting action of the bits is water-jet assisted. A tunneling machine, often shielded, designed to work in a wide range of conditions such as hard rock or soft ground with only an exchange of bits, is called a full-face hybrid boring machine. Machines designed to work in blocky ground where wide joints and fissures are filled with clay may have breasting plates and rings to prevent blocks from being caught between the cutters and clogging the muck removal system (S4).

Planned Approach to Meeting Objectives - Machine cutter-head and power-train designs will be obtained from as many companies as possible. The people who have used these machines will be interviewed and their recommendations will be incorporated into the design. Hughes Tool Company, Dresser Industries, and Robbins Company have offered help toward this end. Other companies are still being contacted. Foreign designs will also be considered. Germany, Japan, and Great Britain will be visited to observe their machines in operation.

After a complete literature search, various bit manufacturers will be contacted and bits for tests will be obtained. One of the bit types receiving considerable attention at the present time is the Polycrystalline Diamond Compact (PDC) bit. This bit uses a shear (drag) cutting action and s adaptable to both soft and medium-hard formations. PDC bits have been sed with considerable success in petroleum drilling and should be adaptable o tunnel boring technology (P3, P7). The drag-bit concept will allow it-tooth replacement from inside the boring machine while the more onventional disk cutters may require access to the front of the machine, hich may prove difficult. Single-tooth cutting studies are needed to help redict the performance of this bit in different rocks, under mixed-face onditions, and under various pore pressures and in-situ stress conditions.

In recent years, progress has been made in rock-cutting rates through the use of water-jet assisted bits. Researh currently underway in the Mining Engineering Program at Texas A&M University will be adapted to the proposed research. Laboratory tests will be performed to determine the value of water-jet assistance when cutting with a single PDC tooth.

Tooth indentation and cutting studies will provide information required for the development of the cutter head. Rock fragments cut by the individual teeth need to be flushed into a collection system in order to avoid recutting the same rock, which lowers the penetration rate, and to initiate the muck-removal process. The head design will require basic information on bit placement, force on the bit, rotational speed, and bit hydraulics. We propose to design and construct a micro-drill assembly capable of performing the needed laboratory-scale tests using two or three different bit designs. The micro-drill will probably be similar to that described by Karfakis (K1). A computerized data-acquisition and control system is currently available in our laboratory and will be utilized in this task to control the system and monitor the basic parameters. A sieve analysis will be run on the cuttings from each test and compared with requirements for making an acceptable slurry for the muck-removal system.

It is well known that oil well drilling rates increase significantly when formations are encountered that have high pore-water pressure. In these formations the effective stress (total stress minus the pore-water pressure) is very low. In fact, a high drilling rate signals the driller to increase the mud weight of the circulating fluid if an oil well blow-out is to be prevented. It is also well established that any formation can be hydrofractured by increasing the pressure in the bore hole fluid and that this can sometimes cause a loss of circulation. It is this hydrofracture process that is used to increase the permeability of a formation to stimulate better oil and gas production.

If deep formations can be hydrofractured, there is no reason that shallow formations in front of a tunnel boring machine cannot be hydrofractured to increase the drilling rate. This technique will be tested during the time the cutter bits are being researched, and if it proves to be feasible, the probe in front of the cutter head will be designed to increase the pore pressure in the hard rocks sufficiently to cause hydrofracture.

Tunnels penetrating permeable water-bearing formations under pressure may require some method to balance this pressure unless the water table can be lowered by drainage or the formation can be grouted. Three methods have been used to balance the water pressure: (1) internal compressed air pressure either at the tunnel head or in the complete tunnel, (2) water or slurry pressure at the face of the tunnel, and (3) muck or earth pressure generated by muck-flow restriction from the tunnel face. These same techcniques are used to support low-strength formations or tunneling ground and to prevent inflow of gas. Since the muck is to be transported hydraulically out of the tunnel, the water inflow will be controlled by pressurizing the water scouring the tunnel face to remove the cuttings. Indeed, in soft ground situations water inflow can be used in CUTS to aid the much removal process.

TASK GROUP 2.1. - CONCRETE MATERIALS HANDLING AND TRANSPORT

TASK GROUP 2.4. - MUCK HANDLING AND TRANSPORT

Objective - The objective of this program is to design and operate hydraulic and pneumatic transportation systems for muck and concrete materials. The transport systems are intimately coupled to the cutting head (muck scouring and injection) and use the pipelines in the tunnelling. A prototype system will be built during the first year of the project tested in surface operation with concrete pipelines.

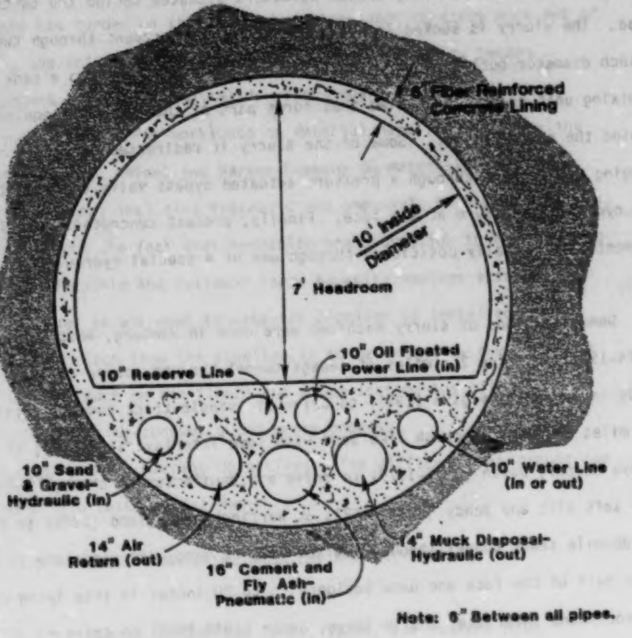
Background - Muck removal in tunneling often limits the rate of advance, and is also a source of downtime which further reduces system performance. Likewise, support of the tunnel bore and advance of material-handling facilities further increases downtime and lack of tunnel progress. Recently developed tunnel boring machines are capable of advancing the face muck faster than the traditional muck removal and other component operations can be advanced. Muck removal competes with the transportation of lining material to the point that conventional transportation systems such as rail, rubber-tired vehicles, and conveyors become limiting factors in tunnel advance. The tunneling operation becomes, by necessity, an inefficient cyclic system, since the tunneling machine must stop frequently to extend rails or pipeline when the machine has moved forward by one rail or pipeline segment length (P5, P6).

Change from a cyclic to a near-continuous process can be accomplished by use of a hydraulic or pipeline transport system. Difficulties inherent with conventional pipelines (including the cyclic addition of pipe to match tunnel advance) are overcome with the CUTS system. In addition to muck removal, transportation of the lining material in raw material form (sand, gravel, cement, reinforcing fiber, fly ash, and water), is accomplished by continuously cast pipelines as shown in Figure 9. The cyclic bottleneck in current tunneling is thereby entirely removed.

Since both the muck removal and transportation of lining ingredients will be transported hydraulically or pneumatically, the basic research and design of these systems is almost identical; consequently, we intend to elaborate on these task groups in a combined way.

Hydraulic transport (pipeline systems) has been used under a variety of conditions to convey over 140 different materials including limestone, alumina, clay, coal, uranium, gold slime, gravel, magnetite, sand, shale, phosphate rock, and bauxite (G3, C2). Research has been done both on hydro- and air-transport in many countries including the United States, the USSR (T9), France, England, Australia, Poland, South Africa, Japan and West Germany (T3, W1). A quarterly report called "Solid-Fluid Abstracts" contains brief descriptions of hydraulic transportation research being conducted around the world.

The hydraulic transportation system in tunneling offers numerous advantages over other systems. The modern slurry machine was developed in response to tunneling problems encountered with wet running ground that lies well beneath the water table. It is usually called a slurry shield or a muck circulation shield and has been utilized in many projects in Japan (M4), England (B7) and West Germany (H4, K3). Typical of this type of system is the Universal Soft-Ground Tunneling Machine of Markham and Company, United Kingdom. The muck from the face when combined with water is turned into a slurry by the cutting action of the arms, with the water



6" Fiber Reinforced Concrete Lining
10' Inside Diameter
7' Headroom
10" Oil Floated Power Line (in)
10" Reserve Line
10" Sand & Gravel-Hydraulic (in)
10" Water Line (in or out)
14" Air Return (out)
14" Muck Disposal-Hydraulic (out)
16" Cement and Fly Ash-Pneumatic (in)
Note: 6" Between all pipes.

CROSS SECTION OF TUNNEL LINING WITH CAST-IN-PLACE PIPES

Figure 9.

supply and the hydraulically driven agitators situated behind the cutter head. The slurry is sucked from the excavation compartment through two 6-inch diameter outlet pipes. These pipes convey the slurry to a tank and a mixing unit mounted on a sled that forms part of the auxiliary equipment behind the shield itself. Some of the slurry is redirected back into the digging compartment through a pressure actuated bypass valve that maintains the hydraulic pressure at the face. Finally, precast concrete tunnel lining segments are manually positioned through use of a special hydraulic crane (S4).

Demonstrations of slurry machines were done in Hamburg, West Germany (1974-1977) to drive 2.9 miles of sewage tunnel through coarse and fine sands in Antwerp, Belgium (1977) to drive six single-track tunnels totaling 2.4 miles in length through fine sand with some interlayers of clay; at Nagoya Harbor, Japan (1976-1979) to drive a 1.3-mile tunnel through solid, very soft silt and sandy gravel (K2), at Warrington, England (1976) to drive a 0.88-mile sewer tunnel through a mixed face of sand with sandstone in the lower half of the face and hard boulders up to 20 inches in size lying on the rock/sand interface; and in Tokyo, Japan (1978-1980) to drive a 0.66-mile waterworks tunnel through fine sand. However, hydraulic transportation has been applied in hard-rock tunneling practice to only a very limited extent, exclusive of the slurry machines discussed above. Examples are the St. Peters sandstone in the Twin Cities area of Minnesota, the Radau Tunnel in the Hartz Mountain of Lower Saxony in West Germany (H4) and the Azotea water tunnel in the western United States (J1).

The operational experience listed above has shown that hydraulic transport can provide the large capacity and continuous muck removal required for tunneling operation. Research such as the U.S. Department of Transportation has funded on the use of hydrotransport to carry muck out of tunnels (B8), the University of Minnesota to document the St. Peters sandstone project and to develop solids-water separation methods, the Colorado School of Mines for workshops on Material Handling for Tunneling Construction (M8, T3), Holmes and Narver Company on materials-handling methods for tunneling, including hydraulic and pneumatic transport (D2, D3), undoubtedly supports the fact that hydraulic transportation in tunneling is one of the most feasible and reliable large capacity haulage systems. Note, however, that in all uses to date the pipeline is installed in discrete lengths. Each time the pipeline is to be extended, the line must be opened (dumping muck on the floor) and a new section installed. CUTS will eliminate this time-consuming and messy process.

Planned Approach to Meeting Objectives - The different task groups can be broken down into tasks as follows:

TASK GROUP 2.1. - CONCRETE MATERIAL HANDLING AND TRANSPORT

2.1.1. System of Surface Tanks, Silos, and Bunkers With Fluidizing Beds

2.1.2. Surface Blowers and Injectors to Propel Cement and Fly Ash

2.1.3. Surface Pumps and Injectors to Propel Sand, Gravel, and Wire Fibers

2.1.4. System for Material Pickup at Surface

2.1.5. Piping for Pressure, Abrasion Resistance, and Flow Rate (Concrete Materials in Air or Water)

2.1.6. Air-Lock Feeders and Metering Devices.

TASK GROUP 2.4. - MUCK HANDLING AND TRANSPORT

2.4.1. Piping for Pressure, Abrasion Resistance, and Flow Rate (Muck in Air or Water)

2.4.2. Booster Pumps and Blowers

2.4.3. System for Surface Muck Separation

2.4.4. Muck-Pickup System

2.4.5. Muck-Disposal System

It must be recognized that the different tasks stated above are very much interrelated. The equipment for most of the tasks is readily available and will require only limited modification.

The work of these task groups will be organized as follows: 1) obtain engineering data for the design of a hydraulic-pneumatic transportation system for rapid tunnel construction.

2. Laboratory tests to supplement existing pipeline design data for the design of water, air, and power supply requirements.

3. Pipeline tests to obtain the large-scale data for the optimum design and operation of the pipeline.

4. Selection and design of the major parts of the system such as injectors, feeders, separators, pumps, blowers, etc.

Laboratory Research - Laboratory tests are required to fully understand the effects of various parameters on the system performance. Specific studies will include:

--Particle settling velocity
--Some rheology studies
--Size distribution
--Specific gravity
--Dewatering rate
--Pipe material (concrete) wear and resistance
--Wheel stand studies on
a) Effect of mixtures (bentonite, polymers, etc.)
b) Effect of fines

Pipeline Research Program - The purpose of the pipeline research program is to define pipe friction loss and optimum operating conditions for hydraulic (and water-air mixture) haulage systems for tunneling equipment. The intent of this program is to identify the precise effect of each variable by holding the others constant. Actual concrete pipes of the design for CUTS will be used in these tests.

The tests will include:

Effect of	Means of Measurement
Pipe diameter	Operation of the Ocean and Hydraulic Engineering Program 4-, 6-, and 8-inch pipeline systems at Texas A&M University
Pipe roughness	Starting and ending rock tests with clear-water runs
Concrete pipe and vertical section	Headloss measurements in 45-degree downsection and vertical section, etc.
Particle-size distribution	Multiple pipeline tests on at least three different rock types and sizes
Concentration	Ratio of rock feed to water, changed by steps during pipeline operation
Safety	Sudden shut-down and re-start tests, artifically caused cavitation tests
Velocity	Velocity changed by steps during pipeline operation

Water-air mixture	Pipeline operation by continuously pumping and releasing air into the system

Studies on Selection and Design of Equipment - Technical literature reviews will be conducted on availability and reliability of pumps, feeders, crushers (if required), separators, and instrumentation. Appropriate equipment is readily available on the market.

--Pumps: Many coarse-particle transport systems use centrifugal pumps to ingest premixed slurry and to boost pressure at intervals along the pipeline. Both centrifugal and positive displacement pumps will be considered for the several applications in CUTS.

--Feeders: A number of feeders are available for feeding coarse-particle slurries into pipelines. However, most of them are too large for tunneling equipment. We intend to study pipe feeders such as the ones marketed by Hitachi and Transflux International, and rotating pocket feeders such as those made by Kamyr Corp., that could be used in tunnel-muck haulage systems. A number of other concepts such as a portable sealed-screw feeder will also be studied. For muck pickup the jet pump system and helical inducer slurry injector will be investigated.

--Crushers: One disadvantage of hydraulic transport is that maximum- and small-particle size must be controlled to suit the pumps and pipeline. Some control over particle size can be exercised by cutter design, but additional control may be required by installation of crushers ahead of pumps and pipeline.

--Separators: This equipment is used to separate the solids from the water or, air after delivery through the pipeline. The obvious choices are screens, sieve bends, and cyclones. For application to underground tunnel excavation, however, each technique presents difficulties due to the space requirement of existing designs. Considerable effort will be devoted to developing compact designs for the separators that will be located on the boring machine.

--Pipelines: The research in this area will be two-fold:

a) The pipeline must be sized to provide sufficient capacity to handle production at the lowest practical velocity consistent with slurry entrainment;

b) Slurry transportation in concrete pipelines has almost no experimental data. Addition of a continuous roll-process welded steel inner lining will be studied.

Leakage or rupture of hydraulic pipelines has more serious consequences underground than on the surface. Therefore, safety features must be designed into the system. Pressure sensors and/or flow sensors will be implemented.

--Instrumentation: Instrumentation for CUTS will use standard equipment except in a few cases. Some development will be required for suitable pressure sensors capable of operating reliably in slurry. Also, concentration sensing for feed and flow control will require development, especially if there are wide variations in content and concentration level. Gamma-ray gauges will be studied because they may work well for tunnel muck in pipelines.

The Center for Dredging Studies at Texas A&M University operates a large-scale pipeline slurry transportation facility capable of studying three-phase flow of slurries containing water, air and solids to optimize the slurry composition and measure flow properties, entrainment, etc. Alternatively the U.S. Bureau of Mines Pittsburgh Research Center has offered use of its Hydraulic Transport Research Facility for a large scale study. Finally, the following firms are participating in system design:

Fuller Company, Bethlehem, PA: Pneumatic Transportation System and Separators

PSI--Pipeline System Incorporated, Orinda, CA, Muck Gravel and Sand Transportation System Design

Krebs, Inc., Menlo Park, CA; Hydrocyclone and Separators Design

Howard Concrete Pumping, Inc., Venetia, PA; Concrete Pump Design

Kamyr, Inc., Glens Falls, NY; Pump and Feeder Design and Selection

The friction loss and other parameters have been estimated, and the preliminary parameters for the haulage systems are summarized in Tables 3, 4. Data on existing slurry pipelines is shown in Table 5.

Pumps for the muck system will be located in the tunnel. A typical pump which can be considered for the system is the ESY 5809, 16" x 14" max. 6" max solid size, max head pressure 90 psi, max solids 55%, 550 RPM.

The gravel and sand pumping system will be located on the surface. Positive displacement pumps will probably be used for these applications.

Table 3

Pneumatic Transportation of Cement and Flyash

Preliminary Design

Cement and fly ash required to be transported: 0.5 ton/minute

Assumed specific gravity: 2.5

Pipeline; 16" diameter

Air quantity: from 8,000 to 9,000 CFM

Pressure: from 30 to 35 psi

Total energy required: 1200 H.P.

Compressors: Three Fuller Rotary Vane Type 608 Compressors will be required with 400 H.P. each

TABLE 4

HYDRAULIC TRANSPORT OF MUCK, AGGREGATE AND SAND

PRELIMINARY DESIGN

	MUCK	AGGREGATE	SAND
Quantity to be Transported	964 tons/hr	2.5 tons/minute	1.2 tons/minute
Solid Concentration in Slurry	28% by volume ~50% wt.	28% by volume ~50% wt.	28% by volume ~50% wt.
Calculated Total Flow Rate	11.79 ft^3/sec 5292 GPM	1.82 ft^3/sec 817 GPM	0.86 ft^3/sec 410 GPM
Pipeline's Diameter	14 inch	5 inch	3½ inch
Flow Velocity	14 ft/sec	14 ft/sec	14 ft/sec
Calculated Friction Loss	15.8 ft/100 ft. of pipe	24.3 ft/100 ft. of pipe	26.5 ft/100 ft. of pipe
Total Head Required	2670 ft.	4107 ft.	4479 ft.
Maximum Pressure	1160 psi	1780 psi	1940 psi
Power Required	5178 H.P.	1230 H.P.	634 H.P.

TABLE 5

DATA ON EXISTING SLURRY PIPELINES

1. **Mobil Chemical Company**
(Nichols, Florida) Phosphate Rock

Length: 9000 ft.

Pipeline: 18" diameter

Power, Pumps: 3 centrifugal pumps
2 pumps 500 H.P.
1 pump 800 H.P.
1 pump 1,250 H.P. (stand by)

Velocity: 12 ft/sec

Slurry: 35% wt or 19.4% by volume

Specific gravity: from 1.25 to 1.35

Rock specific gravity: from 2.7 to 2.85

Friction loss: 3.5 ft of slurry/100 ft of pipe

Size Distribution of Slurry

10%	from 8" to 1/2"
10%	from 1/2" to 20 mesh
13%	from 20 mesh to 35 mesh
27%	from 35 mesh to 150 mesh
40%	-150 mesh

2. **International Mineral and Chemical Corporation**
(Bartow, Florida) Phosphate Rock

Length: 25,000 ft.

Pipeline: 20" diameter

Power, Pumps: 6 pumps--44" x 52" centrifugal
Motors: 900 H.P. to 1250 H.P./pump

Velocity: 15.5 ft/sec to 17.5 ft/sec

Slurry: from 30 to 40% wt or from 14 to 20% by volume

Specific gravity of slurry: 2.6 to 2.7

Friction loss: from 3 to 5 ft of slurry/100 ft of pipe

Size Distribution of Slurry:

1%	from 8" to 3/8"
4%	from 3/8" to 6 mesh
8%	from 6 mesh to 16 mesh
13%	from 16 mesh to 35 mesh
46%	from 35 mesh to 150 mesh
28%	-150 mesh

TASK GROUP 2.2. - CONCRETE MATERIALS SEPARATION, MIXING, AND INJECTION

Objectives - The objectives of this Task Group are

1. To design a system to separate the concrete materials from the fluids that have transported them to the tunnel head.

2. To design a system to meter and mix these materials and transport them pneumatically to the concrete pumps.

3. To design a system of pumps to inject concrete into the slip forms.

Background - Particulate-fluid mixtures are usually separated by either screens, decantation, settling tanks, or cyclones. Such devices are used throughout industry. Separated particulates are often metered through gates onto conveyor belts, but the best control comes by using air-lock feeders. They are attached to the bottom of fluidized tanks that store the particulates. Mixing of particulates usually is handled by tumbling in rotating drums, but screw or auger mixers are becoming more prevalent. Dry concrete is often blown into place as shotcrete or gunite, and wet concrete is often pumped using a variety of pumps. The wet-concrete pumps include piston pumps, plunger pumps, Moyno pumps, and peristaltic pumps. Often compressed air is used to move slugs of wet concrete in pipelines. If blockage occurs when pumping concrete, often compressed air is used to restart flow. Concrete has been pumped about 3,500 feet horizontally in five-inch diameter steel pipe. Often concrete is pumped as high as 75 stories in building construction against heads of 1,000 psi.

Planned Approach to Meeting Objectives - The manufacturers of hydrocyclones and water-lock feeders will be contacted during the preliminary design. Dresser Industries, Dorr-Oliver, and the Ohio Rubber

Company (Orthane Division) are some of the companies that are experienced with the dewatering equipment needed. Montgomery Industries International (Jacksonville Blowpipe Division) and Neptune Airpol, Inc. (a subsidiary of Wheelabrator-Fry, Inc.) will be contacted during the design of the pneumatic cyclone and air-lock feeder.

The design of the blower and pneumatic mixers will follow that used in the shotcrete industry. Companies that will be contacted for advice and help with the design include Challenge-Cook Brothers Company and Allentown Company. Other companies such as Eimco, Conspray, Icoma, Reed, and Aliva will also be consulted.

The Barber-Green Company manufactures a truck-mounted concrete batch plant with an auger mixer. It carries 12 cubic yards of material and can mix concrete at the rate of 60 cubic yards per hour. This machine will be evaluated for use as the mixer as a part of the machine.

The concrete pump manufacturers that will be contacted for help in design of the concrete injection system include Schwing America, Inc., who make portable piston concrete pumps, and Robbins-Meyers Company, which builds Moyno progressing cavity pumps. Halliburton Company manufactures its own plunger pumps for high pressure oil well cementing. They will be an industrial partner in the CUTS project and will furnish aid and assistance.

As mentioned before, separation of concrete materials at the tunnel head is complicated by the limited head room in the tunnel. An alternative method of pneumatic transport of the dry-mix concrete in cylindrical tubes through the same pipeline will be studied. This system has been patented by an engineering professor at Georgia Tech and a pilot plant for transporting ore was built in Houston, Texas. In this case no separation and mixing plant would be needed at the tunnel head. The power requirement for such a pneumatic transport system would be very low.

TASK GROUP 2.3. - CONCRETE MIX

Objectives - To develop a cost-effective concreting system for the tunnel lining that, while being easily mixed and pumped, will rapidly harden and gain in both strength and abrasion resistance. Setting times of less than 15 minutes with compressive strengths on the order of 1,000 psi in less than one hour will be developed.

Background - Evidence is available to show that the state-of-the-art today is such that "off-the-shelf" products are available to permit meeting the task objectives. Supporting data are provided in references B9, C3, H5, K5, M7, R6, S3, S5. As one illustration, a particularly noteworthy study (R6) conducted by the Transportation Research Board of the National Academy of Sciences reported on the evaluation of a large number of rapid-setting patching materials. Table 6, taken from this reference, summarizes the known information about 24 cementing material systems; at least 6 of these attain 1,000 psi or greater strengths in one hour (at a curing temperature of about 80°F).

The major question, then, is not whether the objectives can be met, but what is the best approach to meeting them.

Planned Approach to Meeting Objectives - For the first year, this phase of the research is divided into the following subtasks:

Subtask 2.3.1.1. - State-of-the-Art Survey

Pertinent literature will be searched for information concerning the development of concreting systems which may meet our objectives. This will be a minimal effort as almost all the major publicly available literature has already been acquired. This will be coupled with an in-depth survey of current industry developments which may offer promise. The survey will be conducted through telephone contacts followed by interviews where necessary.

Subtask 2.3.1.2. - Selection of Current Candidate Systems

From the available concreting systems currently available, about three will be selected for further evaluation. Performance, availability, and cost will be the determining factors utilized to select these candidate systems.

Subtask 2.3.1.3. - Investigation of New Candidate Systems

In this task, participating industries will investigate proprietary concreting systems of their own (at their expense) and submit the results to us for consideration. In particular, Gifford-Hill and Lone Star Industries plan to participate in the investigation and submit findings for our evaluation. Other industries will also be contacted and invited to participate. We will conduct laboratory evaluation of these concreting systems to verify the results obtained by the participating industries.

Subtask 2.3.1.4. - Selection of New Candidate Systems

Based on the results of the previous subtask, about three new candidate systems will be selected for further evaluation.

Subtask 2.3.1.5 - Characterization and Evaluation

The approximately six candidate systems selected in Subtasks 2.3.1.2. and 2.3.1.4. will be brought to Texas A&M University for complete evaluation in the laboratory. They will be compared on the basis of both technical performance in meeting the objectives and cost-effectiveness, and the most nearly optimum concreting system will be selected for use in the tunneling system.

Table 6 (R6)
RAPID-SETTING PATCHING MATERIALS

Brand and Manufacturer	Basic Material	Other Materials	Approximate handling time - minutes at:					Compressive strength/Time at:					Agencies that have used the product
			20 F	40 F	60 F	80 F	100 F	20 F	40 F	60 F	80 F	100 F	
Burke Non-Metallic Grout Burke Conc. Access. San Mateo, Calif.	Portland cement	Special cements	-	-	40	-	-	-	-	-	(73 F) 4000/24 hr	-	-
Exide Resurfacer 100 Atlas Minerals & Chem. Div., ESB Inc. Mertztown, Pa.	Portland cement	Polymers, silica	-	-	-	120	-	-	-	-	1000/ 7 day 4000/14 day	-	-
Exide Resurfacer 200 Atlas Minerals & Chem. Div., ESB Inc.	Portland cement	latex, silica	-	-	-	45-60	-	-	-	-	1000/24 hr 4000/ 7 day	-	-
Fast-Fix Cement *(P)* Custom-Crete, Inc. Dallas, Texas	Portland cement	Calcium sulfate, calcium aluminate	-	40-60	25	15	5-10	-	250/60 min 500/75 min 1000/ 2 hr 2000/ 2 day 4000/45 day	250/20 min 500/50 min 1000/90 min 2000/24 hr 4000/28 day	250/15 min 500/40 min 1000/75 min 2000/24 hr 4000/28 day	250/10 min 500/30 min 1000/60 min 2000/24 hr 4000/ 7 day	Texas
Fix-A-Crete Custom Bldg. Products Bell, Calif.	Portland cement	Barium chloride, latex (optional)	[illegible]	25-35	25-35	25-35	15	-	-	-	1525/60 min 7250/28 day	-	-
Mirament The Seddon Co. Springfield, Ohio	Portland cement	Calcium aluminate	20	-	-	6	-	-	-	385/30 min 400/60 min 3910/24 hr 5500/ 7 day 6040/28 day	-	-	Ind., Ky., & W. Va.; Cities of Pittsburgh and Indianapolis
Set Instant Concrete Set Products, Inc. Macedonia, Ohio	Portland cement	Silica	-	-	12	5	-	-	-	-	[illegible]/ 2 hr [illegible] hr [illegible] day	900/60 min 2000/24 hr	Illinois; Ohio
Sikaset Road Patch *(P)* Sika Chemical Corp. Lyndhurst, N. J.	Portland cement	-	-	-	-	(75 F) 17	-	-	-	-	(75 F) 500/45 min 1000/ 2 hr 2000/ 5 hr	-	-
Fondu Lone Star Lafarge Co. Norfolk, Va.	Calcium aluminate	-	-	15	15	15	-	-	-	-	(73 F) 2200/ 4 hr 5000/ 6 hr 6300/24 hr	-	Calif., La., Ore., Va. and Wash.; FHWA (G.W. Pkwy.)
FS-16 Pre-Krete Pocono Fabricators E. Stroudsburg, Pa.	Calcium aluminate	Fillers and additives	18	11	11	10	8	-	-	-	1430/60 min 2200/ 3 hr 3100/24 hr 4600/ 7 day	-	N.J., Pa., and Va.; Mass. and Pa. Tpks.; Balto. Co. Md. & Nassau Co., N.Y.
Bostik 275 *(P)** The Upco Company Cleveland, Ohio	Magnesia-phosphate	Silica or dolomitic limestone	(20F) 150	-	(55 F) 25	(73 F) 7	(90 F) 5	-	(35 F) 1000/2.5hr 2000/ 5 hr	-	(70 F) 250/30 min 500/45 min 1000/60 min 2000/ 2 hr 4000/ 7 day	-	Calif., Ohio, & Wash.; Indianapolis Airport Authority
FC-100 *(P)** Steelcote Mfg. Co. St. Louis, Mo.	Magnesia-phosphate	-	-	10-15	-	7-10	-	-	-	-	2000/ 2 hr 4000/24 hr	-	Ohio

Table 6 - Continued

Brand and Manufacturer	Basic Material	Other Materials	Approximate handling time - minutes at: 20 F	40 F	60 F	80 F	100 F	Compressive strength/Time at: 20 F	40 F	60 F	80 F	100 F	Agencies that have used the product
Set - 45 Set Products Inc. Macedonia, Ohio	Magnesia - phosphate	-	-	30	20	12	6	500/ 2 hr 2000/24 hr	1000/60 min 4000/24 hr	2000/60 min 4000/ 6 hr	2000/60 min 4000/ 4 hr	2000/60 min 4000/ 4 hr	Ill., Ind., Mich., Ohio & Pa.; Cook Co. Ill., Wayne Co. Mich.
Colma Dur LV Sika Chemical Corp. Lyndhurst, N.J.	Epoxy resin	-	-	-	35	16	(90 F) 10	-	(35 F) 2000/24 hr 4000/36 hr	1000/7 hr	(75 F) 1000/ 4 hr 2000/4.5 hr 4000/ 6 hr	(90 F) 1000/3 hr	Missouri, N.J., Pa., & Virginia; Corps of Engineers
Conu/Crete and Conu/Crete FS Con/Chem, Inc. Gardena, Calif.	Epoxy resin	Bauxite	240	120	60	30	15	-	-	250/ 3 hr 500/ 6 hr 1000/ 8 hr 2000/10 hr 4000/16 hr	250/ 2 hr 500/ 3 hr 1000/ 4 hr 2000/ 8 hr 4000/10 hr	500/60 min 1000/ 2 hr 2000/ 3 hr 4000/ 5 hr	Cuyahoga Co. Ohio; Port Auth. N.Y. & N.J.
Exide Surfacer 300 Atlas Minerals & Chem. Div., ESB Inc. Mertztown, Pa.	Epoxy resin	Asphalt, silica	-	-	45	30	10	-	-	4000/24 hr	250/ 2 hr 500/ 4 hr 4000/24 hr	250/60 min 500/ 2 hr 1000/ 6 hr 4000/12 hr	-
Tufchem (Epoxy) Grout Pennwalt Corp. Philadelphia, Pa.	Epoxy resin	-	-	(50 F) 180	180	60	60	-	(50 F) 17,500/ 7 day	17,500/ 5 day (Min. setting temp.: 50 F)	17,500/ 2 day	17,500/ 1.5 day	-
Gold Label *(P)* Preco Plainview, N. Y.	Polyester resin	-	120	120	5-120	18-75	10-40	4000/6 hr	4000/90 min	4000/90 min	4000/60 min	4000/60 min	New York; NYC Transit Authority
Radgrout-H^{r} Road & Industrial Concrete Radiation Tech., Inc. Rockaway, N. J.	Polyester resin	-	60	35	40	15	5	10,000/ 90 min	10,000/ 70 min	10,000/ 40 min	10,000/ 30 min	10,000/ 10 min	New York; Pa. Tpk.; Port Auth. NY & NJ; Triboro Bridge & Tun. Auth.; City of Phila.
Vitrobond Atlas Minerals & Chem. Div., ESB Inc. Mertztown, Pa.	Sulfur	Silica	(Hot-melt material)					-	-	-	4000/ 5 min	-	-
Duracal *(P)* U.S. Gypsum Co. Chicago, Ill.	Calcium sulfate	Portland cement	-	35-40	20-35	20-35	15-30	-	2000/60 min	2000/60 min	2000/60 min 4000/ 3 day 5600/ 7 day 7200/28 day	2000/60 min	Colo., Conn., Del., Ga., Mass., N.Y., Okla. Texas, & Va.; Illinois Tollway.
Mari-Crete Atlas Minerals & Chem. Div., ESB Inc. Mertztown, Pa.	Calcium sulfate	Portland cement, silica	-	-	10-15	3-5	-	-	-	-	-	500/ 8 hr 1000/16 hr 2000/24 hr 4000/48 hr	New York; Virginia
DP Concrete Additive Pennwalt Corp. Philadelphia, Pa.	-	-	-	-	-	-	-	(Accelerating additive for any patching formula. Provides 3:28 reduction in time to strength.)					-
Gill #33 B&P Superbond Gill Chemical Co. Hamlin, W. Va.	-	Calcium chloride	60	-	-	30	-	1000/3 hr	-	1000/2 hr 4000/24 hr	2000/2.5 hr	-	Georgia, W. Va.; U.S. Bureau of Mines

(P) Patented   * Licensee of Republic Steel Corp.   NR Not Recommended
Data from survey of manufacturers, October 1978.

TASK GROUP 2.5. - SURFACE BLOWERS FOR VENTILATION

Objective - To design ventilation system for tunnel.

Background - A minimum of 20 cfm/ft^2 of tunnel face or 200 cfm/man is required for tunnel ventilation (51). The compressors, according to OSHA specification, must be powered by dual sources such as electric motors and diesel engines.

Planned Approach to Meeting Objectives - The design of a ventilation system will not require any new developments. A blowing, exhausting or combination of the two systems will be designed. The cast-in-place pipe in the floor of the tunnel will be used as the air return pipe. Bonanza or Joy mining vane/axial fans or their equal will be used in the design. Typically a 10,000 cfm operating against a head of 2.5 inches of water can ventilate a tunnel of 10 diameter 6 miles long. Air blowers for ventilation will be placed at each shaft.

TASK GROUP 3.1. - STRUCTURAL ANALYSIS

Objective - To develop a transient structural analysis procedure that will account for the interaction of the concrete lining, slip form, and soil so that the required strength of the concrete can be determined and the size of the slip form minimized. The analysis should provide for the determination of displacements and stresses in the concrete lining as a function of time.

Background - During the boring process, the concrete tunnel lining must support its own weight plus the forces exerted upon it by the surrounding soil mass as the slip form is moved forward. The load transfer is transient in nature because the tunnel boring will be continuous; the boring will not stop; therefore, the slip form will always be moving ahead. The required length of the slip form is a function of the boring rate and the rate at which the concrete can carry load. The interaction of the concrete lining, the soil, and the slip form must be established so that the required strength of the concrete can be determined and the size of the slip form can be minimized.

Planned Approach to Meeting Objectives - In this structural system, the effects of inertia are negligible. The transient structural analysis, therefore, can be performed as a quasi-static analysis. The time-dependent parameters will be modified at discrete points in time and will remain constant for the next time-step. The size of the time-step, which will dictate the size of the finite-element mesh, will be dependent upon the rate of the boring process.

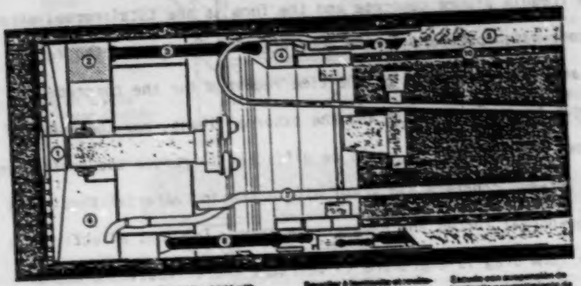
The finite-element model to be used in the analysis will be composed of curved-shell and solid elements. The curved-shell elements will represent the hollow upper portion of the tunnel and the solid elements will be used for the floor and piping portion of the tunnel. Half-symmetry will be utilized when the model is developed; the vertical plane along the centerline of the tunnel is the plane of symmetry. The finite-element analysis will be performed on the Texas A&M University Amdahl computer using McAuto STRUDL, a general purpose structural analysis computer program that includes automatic model generation and graphics capabilities.

TASK GROUP 3.2. - SLIP FORMS

Objective - To design slip forms that support the freshly extruded fiber-reinforced concrete tunnel lining until it reaches sufficient strength to resist the horizontal thrust of the boring machine, its own weight, and the surrounding geostatic stress of the earth. Provisions will have to be made to minimize the drag force between the freshly placed concrete and the surface of the forms so that they can be moved at the same rate as the boring machine.

Background - From 1981 to 1983 Boyce, *et al.*, at Foster-Miller Company designed and tested a model of a tunnel-lining machine that extruded fiber-reinforced concrete lining in steel pipe (B9). In 1981 a consortium of German companies demonstrated a system very similar in concept to a Soviet system (B9, T2). This German system is now being used in the Frankfurt subway tunnels (T7), and its use is advertised by Hocktief in *Tunnels and Tunnelling* (T11). Figure 10 shows the system. The Japanese have developed a similar system although the cement used in the concrete is unsaturated polyester resin (T6). The Foster-Miller design reduces the normal force on the form just before it is pulled forward. This is accomplished in a longitudinal segmented form by closing a bridged slot. Hydraulic cylinders cause the slot to close so that the circumference of the form changes enough to separate the concrete and the form in the event of a shutdown when the forms must be stripped. Foster-Miller also studied various methods of reducing form drag. One of-the most promising methods may be to increase the pore pressure in the concrete after placement and compaction so that the effective stress (total stress minus pore pressure) is reduced to zero. Presently, large-diameter concrete is being slip-formed in trenches at a rate of 700 feet per eight-hour shift (R1).

Extruded concrete lining with steel fibres



Bentonitschild mit extrudiertem Ortbetonausbau unter Zusatz von Stahlfasern	Bentonite shield with extruded concrete lining reinforced by steel fibres	Bouclier à bentonite et revêtement en béton à fibres d'acier extrudé	Escudo con suspensión de bentonita y revestimiento de concreto con fibras de acero
1. Schneidrad	Cutter head	Rotor tranchant	Rueda cortante
2. Druckluftpolster	Reservoir of compressed air	Réservoir à air comprimé	Depósito de aire comprimido
3. Vorschubzylinder	Hydraulic shield jacks	Vérins de poussée du bouclier	Cilindros empujadores del escudo
4. Druckring	Pressure ring	Anneau de pression	Anillo de presión
5. Stahlfaserbeton	Steel fibre concrete	Béton à fibres d'acier	Concreto de fibras de acero
6. Bentonit	Bentonite	Bentonite	Bentonita
7. Förderleitung	Discharge pipeline	Conduite d'évacuation	Tubería de descarga
8. Stirnschalungszylinder	Hydraulic jacks for the front form	Vérins pour le coffrage frontal	Cilindros hidráulicos para el encofrado frontal
9. Gleitende Stirnschalung	Sliding front form	Coffrage frontal coulissant	Encofrado frontal deslizante
10. Stählerne Umsetzschalung	Demountable steel form	Coffrage métallique démontable	Encofrado de acero desmontable

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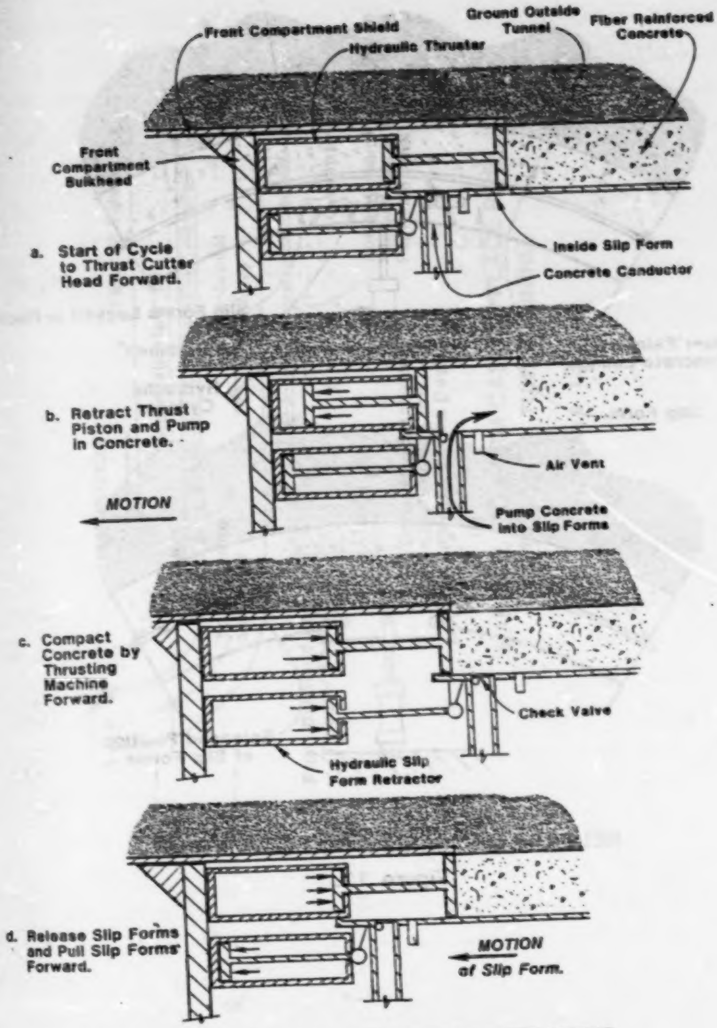
JUNE, 1984 p. 64.

Figure 10.

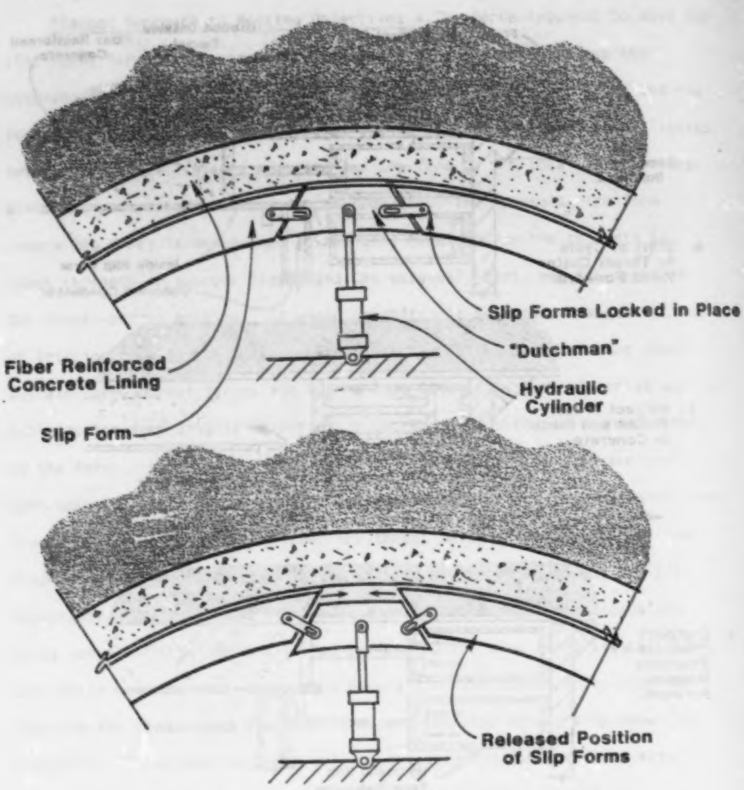
Planned Approach to Meeting Objectives - The force required to move the slip forms forward depends on the effective normal stress between the concrete and form, the coefficient of friction between the concrete and the form, and most important, the area of the form. The effective normal stress between the freshly placed concrete and the form is the total normal stress minus the pore-water pressure in the concrete. The length of the form (hence its area) is determined by the time required for the concrete to reach strength to support itself and the external loads, and the speed of the tunnel-boring machine. It would be difficult to reduce the coefficient of friction between concrete and steel with a coating material that could sustain large normal forces and have a long life. The most effective way to minimize the form drag is therefore to decrease the effective normal stress on the forms. This can be accomplished in three ways: (1) increase the pore-water pressure in the concrete after the machine has thrust against the freshly placed concrete, (2) lower the thrust between cutter head and the fresh concrete momentarily while the slip forms are being moved, and (3) change the diameter of the slip forms a small amount while the forms are being moved. The scheme envisioned for moving the slip forms and thrusting the cutter head forward is shown in Figure 11. The scheme envisioned for changing the diameter of the slip forms and the pipe mandrels is shown in Figure 12. Three bearing types will be investigated for the floor slip form. They are roller bearings, air bearings, and Teflon surfaces.

The drag resistance of the freshly placed concrete on steel and Teflon will be measured in a direct-shear testing machine as a function of the normal effective stress. After these laboratory tests, a slip form to


Front Compartment Shield
Ground Outside Tunnel
Fiber Reinforced Concrete
Hydraulic Thruster
Front Compartment Bulkhead
a. Start of Cycle to Thrust Cutter Head Forward.
Inside Slip Form
Concrete Conductor
b. Retract Thrust Piston and Pump in Concrete.
Air Vent
MOTION
Pump Concrete into Slip Forms
c. Compact Concrete by Thrusting Machine Forward.
Check Valve
Hydraulic Slip Form Retractor
d. Release Slip Forms and Pull Slip Forms Forward.
MOTION
of Slip Form.

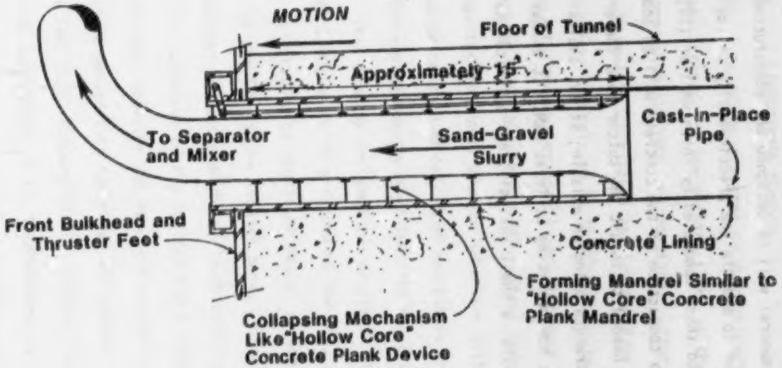
FOUR STEPS OF CYCLE TO EXTRUDE CONCRETE LINING AND THRUST CUTTER HEAD FORWARD.

Figure 11.


Slip Forms Locked in Place
"Dutchman"
Fiber Reinforced Concrete Lining
Hydraulic Cylinder
Slip Form
Released Position of Slip Forms

RELEASE MECHANISM FOR SLIP FORMS

Figure 12.


MOTION
Floor of Tunnel
Approximately 15'
Cast-in-Place Pipe
To Separator and Mixer
Sand-Gravel Slurry
Front Bulkhead and Thruster Feet
Concrete Lining
Forming Mandrel Similar to "Hollow Core" Concrete Plank Mandrel
Collapsing Mechanism Like "Hollow Core" Concrete Plank Device

MANDREL TO FORM CAST-IN-PLACE PIPE
IN FLOOR OF TUNNEL LINING.

Figure 13.

cast concrete around a pipe mandrel will be designed and constructed so that surface tests can be conducted to measure the practicability of the system. These tests will be similar to those conducted by Foster-Miller (T2). The load on the slip forms due to compaction of the concrete will be about 100 psi or one-half the pressure needed to thrust the cutter head forward. The forms will be designed for strength using an existing stress analysis program such as McAuto STRUDL now operating at Texas A&M. It allows a three-dimensional frame analysis, a shell analysis, and a finite-analysis with graphics interaction.

TASK GROUP 4.1. - DIRECTIONAL CONTROL

Objective - To design a system to automatically detect the distance, direction, and attitude of the machine (TBM) so that the computed position can be compared with the required position. After the position comparison, a new attitude must be calculated and instructions transmitted to the hydraulic thruster controls so as to automatically keep the TBM on course.

Background - Optical transit lines, and more recently passive laser beams, have been used to locate a TBM. Steel tapes and electronic distance measuring devices have been used to determine distance. Attitude has often been ignored or determined only from successive position determinations.

The John Mawlem Company used laser in the Picadilly-Heathrow tunnel in 1972 (R2). This company designed two devices - the JM Tunnel Laser and the Laser Beacon 2900, which is produced in the U.S. by Laser Alignment, Inc. A pentaprism is attached to the laser Beacon system to determine the squareness of the TBM to the line of bore. Also, optical inclinometers called "Inogons" are attached to the machine to measure roll of the TBM. A target grid is attached to the TBM for the aligned laser beam to illuminate, so that the (TBM) operator can read off errors in machine position so that the TBM can be guided back to proper alignment. To drive a tunnel around a curve, the Carl Zeiss Company of East Germany has built a small, light laser to fit on the telescopes of its theodolites. In Japan Sokkisha has built a machine combining a small laser and a ten-second theodolite (R2).

The Zed Instrument Company of Surrey, United Kingdom has developed an electro-optic target mounted on the TBM. The target, when activated by the laser beam, measures the horizontal and vertical displacement and the angle of incidence of the laser beam. This last measurement is the attitude or yaw angle. The roll about the horizontal and vertical axes is measured by an inclinometer unit. This information is processed by a control computer. The computer also calculates the corrections required to get back to the required course. This system is now being used in the boring of the Frankfurt, Germany subways.

Planned Approach to Meeting Objectives - During the first year, the guidance and control system will be designed in detail and some component development will be made. During the second year the main components will be purchased and assembled into a practical system. The heart of the guidance system will likely be a Zed TG 260 laser tunnel guidance system. Course correction information will be used as a feedback signal to control the motor pumps and valves which will control the advance of the TBM. Several Optel Precision Beam Deflectors (PBD) will be used to redirect laser beams around a curve so as to follow the TBM around a considerable arc before resetting the laser. The PBD is a very simple, dual-matched optical prism manufactured in the United Kingdom (M2). A standard Hewlett-Packard Electronic Distance Measuring device (EDM) mounted on a theodolite will be used to allign the laser system and to measure the distance traveled. The electronic signal for the distance measurement will also be fed into the tunnel control computer to monitor TBM advance.

GROUP 4.2. - FLOW-RATE DETECTION AND CONTROL

Objective - To design a measuring and feedback system to control the s and thrusters so as to maximize the speed of the Tunnel Boring ne (TBM) using off-the-shelf equipment.

Background - There are many pumps, blowers, electric motors, hydraulic s, and hydraulic thrusters in the tunneling system to be automated. All be started, stopped, and regulated to prevent overloading and the king down of any subsystem. The motors, pumps, and thrusters that must ontrolled with magnetic switches, solenoid valves, and other electrical ces are as follows:

1. Cutter head thrusters and compactors
2. Cutter head guidance hydraulic thrusters
3. Torque electric motors for cutter head (variable speed)
4. Forward pump for muck scour
5. Water pump motor for jet-assisted bits
6. Water pump motor to pressurize formation through probe
7. Torque electric motor for probe (variable speed)
8. Air blower for core removal
9. Booster pumps for cuttings removal
10. Surface blowers to pressurize tunnel
11. Water pump motor for sand, gravel, and steel fibers
12. Air blowers for cement and fly ash
13. Motors for air-lock feeder to meter in solids into fluids for transport
14. Elevator motors to load feeder tanks for concrete supplies
15. Air blower motors to fluidize the feeder tanks for concrete supplies

16. Hydro-lock feeder motors at cyclones to separate sand, gravel, and steel fibers from water
17. Air blower to transport blended concrete materials to concrete pump
18. Motors for concrete pumps to inject concrete into forms
19. Water pump to induce water into concrete pumps
20. Water pump to increase pore pressure in concrete before releasing forms
21. Pump motor for form release
22. Hydraulic cylinders to pull slip forms forward

The pressure flows, motions, and rotation rates that must be measured to control the motors, pumps, and thrusters are as follows:

1. Cutter head thruster pressures
2. Cutter head rotational speed
3. Cutter head torque
4. Velocity of muck as it leaves cutter head
5. Percent solids of muck in slurry
6. Pressure in water before and after it leaves cutter head
7. Pressure in water for jet-assisted bits
8. Pressure in water for hydrofracture of formation ahead of cutter head
9. Air pressure in probe air stream
10. Air pressure in tunnel and in air lock
11. Pressure in water carrying concrete materials
12. Velocity of water carrying concrete materials
13. Percent solids in concrete materials in slurry
14. Elevation and weight of solids in all fluidized feeder tanks and separator cyclones on surface and at head to tunnel

15. Speed of rotation of air-lock feeders that meter in solids for transport at surface or at head of tunnel
16. Rotational speed of concrete pumps
17. Presure in concrete being injected into forms
18. Pressure in all thrusters that compact concrete and move cutter head forward
19. Pressure in all cylinders that pull slip form forward
20. Fluidizing air pressure at surface feeder tanks
21. Length of hydraulic thrusters
22. Degree of closure of all valves.

Planned Approach to Meeting Objectives - The vast amount of equipment available to sense and control the motors and pumps will be reviewed. After the pump and motors have been sized, the control plan will be discussed with contractors and manufacturers so that the equipment bought for testing will be the most reliable and maintenance free. The design will take the sensing signals through a control computer that receives signals from the directional controls and the diagnostic probe. The computer will be programmed to control the motors and pumps to get maximum speed and efficiency of the integrated system.

TASK GROUP 4.3. - PROBE

Objective - To design a probe to extend 30 feet ahead of the cutter head to determine the kind and condition of the soil or rock the tunnel will encounter.

Background - Pilot and exploratory holes are often advanced ahead of the main tunnel in drill-and-blast tunneling. However, it is believed that only one TBM has been built with a probe in the center of the cutting head. This Ingersoll-Rand machine used the probe to maintain alignment; it was not a diagnostic tool.

Probing ahead of the tunnel eliminates surprises. For several years Walker-Neer Manufacturing Company has produced a patented dual drill-string drilling machine that allows continuous coring of rock without withdrawing the dual drill pipe from the hole. Air is pumped down the annulus through a diamond core bit to blow the cores up the inside pipe. The 2.5-inch diameter cores are automatically broken into six-inch segments so that they can move around the curved inside pipe through the power swivel in the top of the drilling rig. The cores and/or cutting can be analyzed and the amount of fractures and fissures determined by comparing the length of intact core obtained with the distance drilled. Any other test can be run on the cores as desired.

In the petroleum industry there are many well-logging firms that measure remotely the geophysical properties of the formations by wire lining devices up and down the borehole. The characteristics measured are electrical self potential, electric resistivity, acoustic velocity, diameter or caliper temperature, fluid conductivity, fluid moment, fluid pressure, and all the nuclear ray responses. These nuclear logging techniques include natural-gamma logging, gamma spectrometry, gamma-gamma logging, and neutron logging. From these measurements or logs, good estimates can be made with regard to:

1. Thickness of rock strata and aquifers
2. Porosity
3. Effective porosity
4. Clay or shale content
5. Permeability
6. Fractures and solution openings
7. Water levels and saturation zone
8. Moisture content and pore-water pressure

If the geophysical well-logging devices can be attached to the probe ahead of the cutter face, many or even most of the surprises in tunneling can be prevented. If it proves impractible to attach them to the probe, many of the measurements can be made on the cores taken from ahead of the cutter head.

Planned Approach to Meeting Objectives - A single length of dual pipe with core bit and power swivel will be designed by the Walker-Neer Manufacturing Company in cooperation with the Texas A&M group. Their existing design must be modified to work in the horizontal configuration through the center of the cutter head. During the second year of the project this machine will be built and tested.

The bore hole geophysical devices for formation analysis will be obtained from NL Sperry-Sun Company of Houston, Texas. Their engineers will assist in the effort to attach the geophysical devices to the probe and in the design of the core analyzer. The electronic geophysical data will be transmitted to the computerized data bank and the control system.

IX. SCHEDULING OF TASKS

The phases of the tasks defined in Section VII and discussed in Section VIII have been scheduled as reflected by the chart of Figure 14.

During the first year of the project, effort will focus on a systematic design of the CUTS technology and prototype studies related to those components of the system requiring the most development. Specific hardware development will include materials mixing, transport, and separation, and slip-form structures. The first-year effort will culminate in surface tests of materials-handling and slip-form components.

During the second year, construction and testing will be completed for all components of the system.

During the third year, the system will be assembled and demonstrated under field conditions.

TASKS/MILESTONES

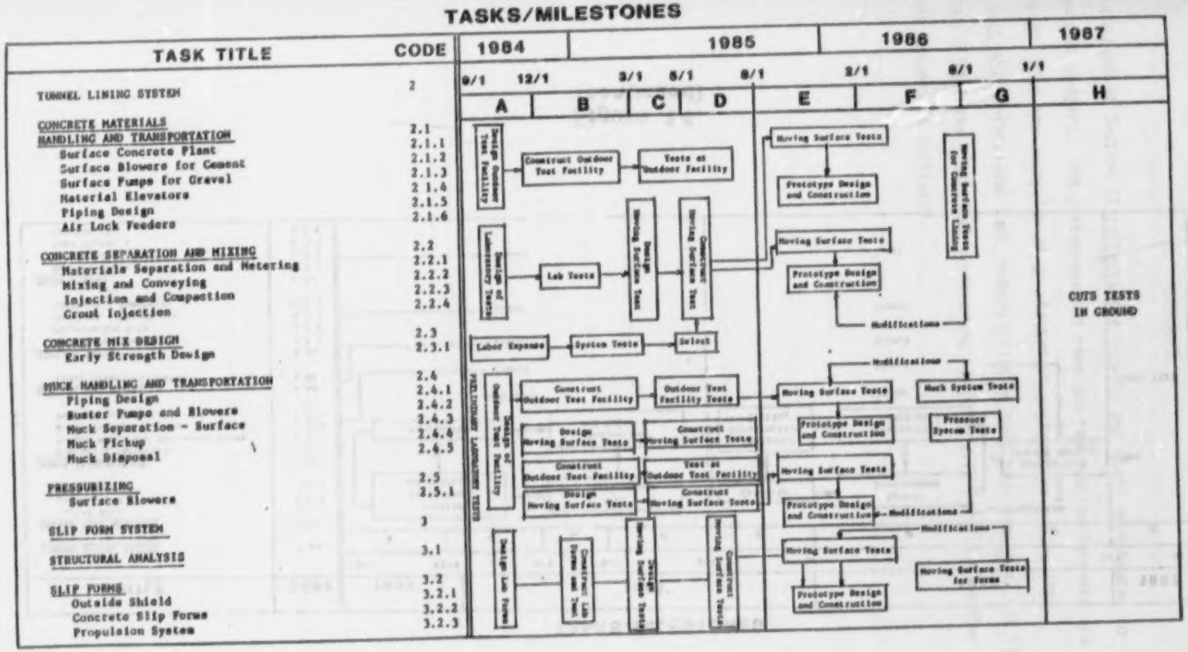
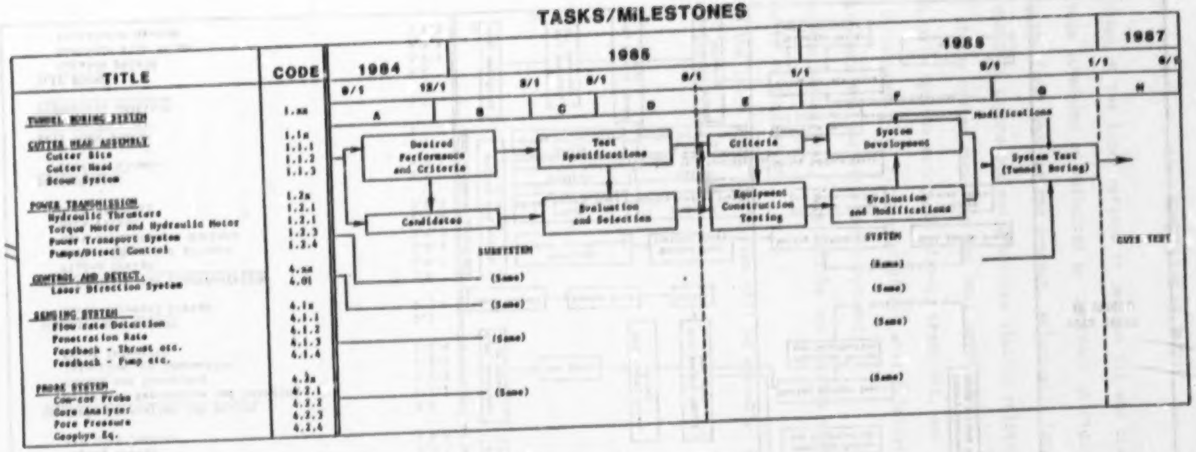

TASK TITLE
CODE
1984
1985
1986
1987
9/1
12/1
3/1
5/1
8/1
2/1
8/1
1/1
A
B
C
D
E
F
G
H
TUNNEL LINING SYSTEM
2
CONCRETE MATERIALS HANDLING AND TRANSPORTATION
2.1
Surface Concrete Plant
2.1.1
Surface Blowers for Cement
2.1.2
Surface Pumps for Gravel
2.1.3
Material Elevators
2.1.4
Piping Design
2.1.5
Air Lock Feeders
2.1.6
CONCRETE SEPARATION AND MIXING
2.2
Materials Separation and Metering
2.2.1
Mixing and Conveying
2.2.2
Injection and Compaction
2.2.3
Grout Injection
2.2.4
CONCRETE MIX DESIGN
2.3
Early Strength Design
2.3.1
MUCK HANDLING AND TRANSPORTATION
2.4
Piping Design
2.4.1
Buster Pumps and Blowers
2.4.2
Muck Separation - Surface
2.4.3
Muck Pickup
2.4.4
Muck Disposal
2.4.5
PRESSURIZING
2.5
Surface Blowers
2.5.1
SLIP FORM SYSTEM
3
STRUCTURAL ANALYSIS
3.1
SLIP FORMS
3.2
Outside Shield
3.2.1
Concrete Slip Forms
3.2.2
Propulsion System
3.2.3
Design Outdoor Test Facility
Construct Outdoor Test Facility
Tests at Outdoor Facility
Moving Surface Tests
Prototype Design and Construction
Moving Surface Tests for Concrete Lining
Design of Laboratory Tests
Lab Tests
Design Moving Surface Test
Construct Moving Surface Test
Moving Surface Tests
Prototype Design and Construction
Modifications
Labor Expense
System Tests
Select
PRELIMINARY LABORATORY TESTS
Design of Outdoor Test Facility
Construct Outdoor Test Facility
Outdoor Test Facility Tests
Moving Surface Tests
Prototype Design and Construction
Modifications
Muck System Tests
Design Moving Surface Tests
Construct Moving Surface Tests
Pressure System Tests
Construct Outdoor Test Facility
Test at Outdoor Test Facility
Design Moving Surface Tests
Construct Moving Surface Tests
Moving Surface Tests
Prototype Design and Construction
Modifications
Modifications
Design Lab Forms
Construct Lab Forms and Test
Design Moving Surface Tests
Construct Moving Surface Tests
Moving Surface Tests
Prototype Design and Construction
Moving Surface Tests for Forms
CUTS TESTS IN GROUND

Figure 14.



TITLE	CODE
TUNNEL BORING SYSTEM	1.xx
CUTTER HEAD ASSEMBLY	1.1x
Cutter Bits	1.1.1
Cutter Head	1.1.2
Scour System	1.1.3
POWER TRANSMISSION	1.2x
Hydraulic Thrusters	1.2.1
Torque Motor and Hydraulic Motor	1.2.1
Power Transport System	1.2.3
Pumps/Direct Control	1.2.4
CONTROL AND DETECT.	4.xx
Laser Direction System	4.01
SENSING SYSTEM	4.1x
Flow rate Detection	4.1.1
Penetration Rate	4.1.2
Feedback - Thrust etc.	4.1.3
Feedback - Pump etc.	4.1.4
PROBE SYSTEM	4.2x
Cow-cor Probe	4.2.1
Core Analyzer	4.2.2
Pore Pressure	4.2.3
Geophys Eq.	4.2.4

TASKS/MILESTONES
1984
1985
1986
1987
9/1
12/1
3/1
6/1
9/1
1/1
9/1
1/1
6/
A
B
C
D
E
F
G
H
Desired Performance and Criteria
Candidates
Test Specifications
Evaluation and Selection
Criteria
Equipment Construction Testing
System Development
Evaluation and Modifications
Modifications
System Test (Tunnel Boring)
SUBSYSTEM
SYSTEM
(Same)
(Same)
(Same)
(Same)
(Same)
(Same)
(Same)
(Same)
CUTS TEST

Figure 14.
(continued)

X. PERSONNEL

The budget of Section XI reflects the faculty and staff anticipated to work on this project. The percentages of time and the task assignments are indicated. With the exception of an electrical engineer to handle TASK Group 4.2, all professional task responsibilities have been assigned. It is anticipated that the electrical engineering position will be filled by the time the project is initiated.

EXHIBIT A

FORMS SUBMITTED TO MAJOR AND MINOR PARTICIPANTS TO INITIATE PARTICIPATION

Statement of Intent to Collaborate in Continuous Unitized Tunneling System Research and Development Program

1. **Name of Company** ______________________________

   Address ______________________________

   ____

2. **Name of Spokeperson (contact person)** ______________________________

   Address ______________________________

   ____

   Telephone ____________________

3. **Nature of participation (major/minor)** ______________________________

4. **(Major participant) Desired task(s) involvement and responsibility* (see attached sheet for role definitions)**

   ____

   ____

5. **(All participants) Annotated list of all areas of potential involvement*: equipment, services, materials, etc. With each area list name, telephone number for contact person.**

6. **Comments/criticism/new ideas on technical aspects of proposal.***

7. **Comments/criticism/new ideas on organization of partnership, definition of roles, contribution requirements, subcontract requirements.***

*** Add additional sheets as needed.**

Please send this partnership response to:

Charles H. Samson, P.E.
Program Manager, CUTS
Civil Engineering Department
Texas A&M University
College Station, Texas 77843

EXHIBIT A (Cont'd.)

STATEMENT OF INTENT

The undersigned organization, through its authorized agent does hereby affirm its commitment and offer to provide the services, work and expertise hereinafter set out in the attached documents upon mutually acceptable terms and conditions.

It is understood and agreed that this research effort, presently referred to as the Continuous Unitized Tunneling System Research and Development Program, is contingent upon availability of funds from the Department of Energy. Should such funds not become available, the undersigned organization shall be free to withdraw said offer upon notification of all parties.

____
Organization

By:____________________________
Name:
Title:
Date:____________________________

APPENDIX A

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APPENDIX B

INVITED PARTICIPANTS IN CONTINUOUS UNITIZED TUNNELING SYSTEM MEETING

July 20, 1984

DOE Participants

Boyce McDaniel
SSC Board of Overseers
U. S. Dept. of Energy

Mahlon Wilson
Los Alamos National Laboratory

Industry Representatives

Elmer Bomke
Brown & Root Development, Inc.

David Bradley
Brown & Root

Ned Broun*
Hughes Tool Company

Kelly Carta
Graham Associates, Inc.

James E. Cook
Gifford-Hill

Elmer Cox
H. B. Zachry Company

Thomas J. Crowley*
Symons, Inc.

Bob Cunningham*
Hughes Tool Company

William Fulton*
Symons, Inc.

Milton E. Goodhart
Hydril Corporation

Karl Jenkins
Hughes-Micon

Bob Johnson
Sperry Sun Division
N. L. Industries

Archie Kotara
Brown & Root

Jerry Lingafelter
Walker-Neer Manufacturing Company

Cecil Lohn
Halliburton Company

John R. Mason
Walker-Neer Manufacturing Company

Yazan N. Sharif
Dresser Industries

H. B. Zachry
H. B. Zachry Company

Panel Reviewers

David Bennett
U. S. Corps of Engineers

Fenwick Carlile
U. S. Bureau of Reclamation

Peter Courtois*
Dayton Superior Corporation

*Unable to attend

Panel Reviewers (cont'd.)

E. O. Mixon
Kenny Construction Company

Kenneth Saucier
U. S. Corps of Engineers

Virgil Schulz
Bean Dredging Corporation

Texas A&M University

Duwayne M. Anderson
TAMU Associate Provost/Research

David R. Basco
Civil Engineering Department

Fred J. Benson
Texas A&M University

Gordon Eaton
TAMU Provost

John A. Fleming
Electrical Engineering Department

Melvin Friedman
College of Geosciences

Lena Fritcher
Civil Engineering Department

Susan E. Gandy
Texas A&M Research Foundation

Steve R. Garrett
Texas A&M Research Foundation

Robert W. Heins
Mining Engineering Department

Teddy J. Hirsch
Civil Engineering Department

Charles Hix
College of Architecture &
Environmental Design

Earl Hoskins
Geophysics Department

Doug Huber
Mining Engineering Department

F. Russel Huson
Physics Department

Ken Kuffner
Arnold, White & Durkee-Attorneys

Eugene L. Marquis
Civil Engineering Department

Christopher Mathewson
Geology Department

Donald McDonald
College of Engineering

Peter McIntyre
Physics Department

Taylor Morgan
Texas A&M University

James K. Nelson
Civil Engineering Department

Texas A&M University (cont'd.)

Mikael Olsen
Civil Engineering Department

Steve Poston
Petroleum Engineering Department

J. T. Rollins
Petroleum Engineering Department

Tibor Rozgonyi
Mining Engineering Department

Charles H. Samson
Civil Engineering Department

George Stukhart*
Civil Engineering Department

Louis J. Thompson
Civil Engineering Department

W. Douglas Tiner
Construction Science Department

Douglas Von Gonten
Petroleum Engineering Department

Harry Whitmore*
Texas Engineering Experiment Station

---

*Unable to attend

APPENDIX C

INDUSTRY PARTICIPATION

As already noted, a number of potential industry participants attended a meeting on the proposed concept, as identified in Appendix B. Subsequently, the concept was presented to other industry representatives to determine their possible interest in the project.

At the time of submitting this proposal, the following commitments have been received:

H.B. Zachry Company San Antonio, Texas	Major participant
Gifford-Hill & Company Dallas, Texas	Major participant
Lone Star Industries Houston, Texas	Major participant
Dresser Industries Dallas, Texas	Minor participant
Walker-Neer Manufacturing Company Houston, Texas	Minor participant
Morrison-Knudsen Co. Boise, Idaho	Minor participant
Atlas Copco Jarva, Inc. Solon, Ohio	Minor participant (strong possibility of changing to major participant)
Halliburton Co. Duncan, Oklahoma	Minor participant

Verbal indications from other organizations of intent to participate have been received and confirmations are expected.

ADDENDUM

to

"CONTINUOUS UNITIZED TUNNELING SYSTEM (CUTS) PROPOSED RESEARCH AND DEVELOPMENT"

RF-84-801

to

DEPARTMENT OF ENERGY

by

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October 1984

BACKGROUND TO ADDENDUM

The basic document submitted on August 17, 1984 proposed a research and development effort toward constructing and demonstrating a "Continuous Unitized Tunneling System (CUTS)." This approach involves substantial departures from conventional tunneling methods, and is pointed toward achieving significant savings in the cost of tunneling for the SSC.

The importance of gaining input from various sectors of the tunneling industry to complement the tunneling expertise of the University staff has been recognized. The original proposal noted a conference held for the purpose of getting opinions from persons representing construction, manufacturing, and materials industries, and from persons in related government agencies.

Since the proposal was submitted, two significant events have occurred:

1. The University has recognized the criticality of the three-year time limitation if the work is to be completed by September 1987 to meet the anticipated start date for construction of the Superconducting Super Collider. Because of the impracticability of reassigning faculty responsibilities during the middle of an academic term, the University, along with the Texas Engineering Experiment Station, established sufficient direct funding to allow the work to begin this past September 1.

2. In order to be assured that opinions on the project were obtained from a broad spectrum of persons in the tunneling field, a second review panel was assembled at Texas A&M on September 16-17, 1984, for an intensive, in-depth review of all aspects of the project. The six consultants were:

   a. Eugene L. Foster, Underground Technology Development, Inc.

   b. James E. Friant, Robbins Company

c. Don Linger, HQ/DNA

d. Russell K. McFarland, TRW, Inc.

e. Wayne McIntosh, Army Corps of Engineers

f. Joseph C. Ungerer, Morrison-Knudsen Company, Inc.

Not surprisingly, there was not unanimity among the consultants on all issues. However, there seemed to be a consensus with respect to these points:

1. There was a general belief that substantial improvements are attainable in several aspects of conventional tunneling, and there was strong encouragement to provide for such opportunities in the proposal.

2. The panel expressed concern that the use of CUTS depends upon the simultaneous functioning of all components, and recommended that the components be "decoupled" where possible so that failure of one component need not halt the tunneling process.

3. The panel questioned whether a single, unitized system could accommodate all types of geology, and recommended that at least two approaches be considered: one for competent soil, and one for soil conditions that are not competent.

4. While considering the first-year funding to be adequate, the panel believed that the funding estimates for the second and third years were low considering the construction and demonstration activities that were planned.

5. While the original proposal did not address the topic of potential savings in contractual procedures, the panel felt strongly that substantial savings could be realized through modification of existing procedures. Views on other aspects of the proposal varied. In order to give as complete a picture as possible of the review, opinions solicited from the panel consultants are summarized in Appendix A.A to this Addendum.

PURPOSE OF ADDENDUM

The purpose of this Addendum is to incorporate into the basic proposal itional elements that are responsive to consultant views for which a sonable consensus exists. In this way the original proposal, combined with e Addendum, will include the following modifications:

1. SCOPE:
   a. CUTS ("Continuous Unitized Tunneling System") research and development (substantially described in the basic proposal) for an improved tunneling approach in soils that are not competent.
   b. SATS ("Surface Assisted Tunneling System") research and development for an improved tunneling approach in soils that are competent.
   c. An enhancement of conventional tunneling approaches through the work related to CUTS and SATS.
   d. Development of a variation of CUTS that would reduce the implications of the "coupled" functioning of components in CUTS.
2. FUNDING:

It is considered that the broadened scope of work can be accommodated in Phase 1 of the project within the amount requested from DOE. Many of the tasks defined for CUTS research and development can be (and already have been for work now in progress) adjusted to accomplish the initial effort toward the added scope items.

With respect to years 2 and 3, however, it is considered that funding requirements will vary markedly according to which concept is selected for the detailed design, development, construction, and demonstration in Phases 2 and 3. It is anticipated that a substantial portion of the costs of Phases 2 and 3 would be subcontracted (cost-plus a fixed fee) by appropriate industrial organizations.

3. INDUSTRY PARTICIPATION:

In developing the industry team members, a very favorable reaction has been received. While several organizations have been in position to join the effort on the basis of a three-year annual commitment of $50,000 plus an average of four senior-level technical staff, in other cases a strong interest has been displayed but with the indication that present economic conditions do not allow an absolute commitment of that magnitude. However, in several instances substantial assistance in various forms has been not only offered but actually given (e.g., detailed plans of tunnel boring machines).

Sufficient discussions have now been held with industrial groups to indicate the merit in pursuing another alternative. Industry participants would be selected on the basis of their interest in providing technical advice, equipment, laboratory facilities, materials, and/or other items. A working Industry Advisory Committee would be established to permit a close working relationship with the University Management/Technical group.

ADDITIONS AND MODIFICATIONS

PROPOSAL COVER PAGE

1. Title: The title of the research proposal, in order to reflect added scope, should read:

   "CONTINUOUS UNITIZED TUNNELING SYSTEM (CUTS)
   AND
   SURFACE ASSISTED TUNNELING SYSTEM (SATS)
   PROPOSED RESEARCH AND DEVELOPMENT"

2. Proposed Duration: 3 years (no change)
3. Amount Requested: $1,100,000 (first year) plus second-year and third-year costs of design, development, construction, and demonstration of selected approach(es).
4. First Year Request: $1,100,000 (no change)
5. Requested Starting Date: 11/1/84 (no change)

ABSTRACT

The additions and modifications to the ABSTRACT should reflect the following:

1. It is proposed to perform research and development during the first year of the project aimed toward producing preliminary designs for two concepts:
   a. For "good" soil conditions - a new "Surface Assisted Tunneling System (SATS)" and
   b. For "poor" soil conditions - a new "Continuous Unitized Tunneling System (CUTS)"

   These concepts would increase tunneling rates substantially and at the same time produce a dramatic reduction in present-day tunnel costs.
2. Phase 1 requires $1,100,000 of FY 85 funds. Funding for years 2 and 3 (Phases 2 and 3, respectively) will be appropriate to the concept(s)

selected for detailed design, development, construction, and demonstration during Phase 2 and Phase 3. The Phase 2 request of $2,800,000 is still considered a reasonable preliminary estimate, but subject to modification depending upon Phase 1 work. For Phase 3, the budget of $1,800,000 is intended as an estimate for personnel and equipment and does not include the cost of contracting for the tunneling demonstration.

3. Contributions from industry would consist of any equipment, materials, technical advice, laboratory testing, designs, etc. that participating organizations might be in position to provide.
4. The project is proposed to begin in November, 1984 and be completed in three years, at the end of which the SATS technique and/or the CUTS technique will have been demonstrated in actual practice.

I. INTRODUCTION

The additions and modifications include the following:

1. The funding for years 2 and 3 should be modified as noted above.
2. Contributions from industry should be modified as already noted.
3. The broadened scope should be reflected.
4. The following points should also be incorporated into the INTRODUCTION:

The purpose of this research effort is to devise ways to reduce the costs of the planned SSC tunnel below present-day costs. There are at least five ways this may be accomplished: (a) minimize owner requirements; (b) select a site to minimize construction costs; (c) utilize the best contractual procedures; (d) develop better methods of tunneling using "off-the-shelf" equipment; and (e) develop new equipment or modify old equipment so that a new tunneling technology can be developed. These five ways to reduce costs are more fully discussed as follows:

(a) Owner Requirements: The owner requirements such as size of tunnel, length of tunnel, depth of cover, spacing of shafts, and the amount the tunnel n deviate from a plane all significantly influence the project cost. Other tems such as requirements for complete watertightness and wall smoothness ill influence costs. Costs will be lowered by building only the minimum ecessary facilities and by making the tolerances as large as possible.

(b) Site Selection: Costs will be a minimum when the site has little urface relief and the geology is soft, stiff, unfractured, and uniform. hese conditions will minimize shaft depths and the need for temporary sup-ort. In fact, if the water table is below the tunnel and the geology is sufficiently stiff and unfractured, no lining may be needed. Of course, sites with running sands, soft, plastic clays, flowing silts, boulder glacial till, and very hard rock should be avoided.

Sites where work on the surface is not hindered in the winter are best. The site should be located where low cost skilled labor, materials, and equipment are available. It is obviously desirable to minimize land costs.

(c) Contracts: Any contract procedure that reduces contractor risk will lower the bid price. This can be accomplished by extensive site investigation, site exploration, and soil and rock testing. Even with the best site investigation, anomalies will be found and the contractor must be protected by a changed-condition clause if low bids are to be expected. There are over 67 kinds of insurance a contractor must carry if protection from unexpected risks is desired. Bid bonds and performance bonds are usually required. The owner must eventually pay for all these costs. By directly assuming the insurance and bonding responsibilities, the owner can reduce the bid price. By carrying minimum insurance and by designing contractor safety measures, the insurance costs can be minimized. Legal costs can often be reduced significantly by anticipating and circumventing disputes, and if this is impossible, prescribed arbitration procedures can minimize legal costs. Complete, workable plans and specifications that detail the work can minimize disputes and lower bid prices. This requires good and expensive engineering, but the overall project cost can be significantly reduced.

There are probably many additional ways to change contract procedures related to quality control and quality assurance that can also reduce costs. In some cases, however, federal or state laws may limit the implementation of cost-cutting contracts.

(d) New Methods of Tunneling Using Off-the-Shelf Equipment: Even though contractors are risk-takers, they are reluctant to bid on a project using unproven equipment and methods. Anything new must be demonstrated, or a manufacturer must guarantee its performance. When shown that off-the-shelf equipment can be combined or used in new, logical ways to reduce costs, the contractor will accept it. However, the contractor's bid price will change only enough to provide an expectation of a successful bid. It is only when several bidders accept the new method that competition occurs and reduced costs result.

(e) New Tunneling Technology: Nearly all innovation in tunneling technology has come from the manufacturers. They have tried to recover their costs of research and development through the price of their equipment. Usually the profits accruing from their work have gone largely to the contractors. Once the innovation is demonstrated, other manufacturers are usually able to imitate, and the original innovator must lower prices to compete. In the end, the owners profit from innovation once enough interested manufacturers and contractors accept the ideas and compete for jobs using the cost-cutting innovation. Most of the government-sponsored tunneling research and development has produced only paper studies. These studies have not had much impact on the industry because no one has produced a working model that could be demonstrated and for which manufacturers could guarantee performance.

The CUTS proposal is an effort to turn the situation around. A radical design is proposed for a machine that would work in good ground; however, it is basically a machine for bad ground. It is proposed to get industry involved so that a system could be built and demonstrated where the different manufacturers would guarantee the performance of the components. If several contractors could be involved in the system design and demonstration to the extent they believed other contractors would bid using the innovation, then bid costs would decrease.

The second review continually emphasized the importance of a good site selection for the SSC, thus enabling a much simpler tunneling system to be developed. In good ground, temporary shoring is not needed and there are no major water-intrusion problems. The boring and lining operations can then be decoupled. Also in a good, nearly level site, many shallow holes can be drilled for support operations. The shallow holes could be used initially for muck removal, ventilation, and power, and later for concrete injection to the tunnel-lining operation. This eliminates much of the expensive shaft construction with long set-up time, and long tunnel transit distances. Such a system could then be developed from off-the-shelf, proven equipment, and several contractors might be induced to bid using the cost-cutting design without a full-scale demonstration.

Thus, for known favorable site conditions, a Surface Assisted Tunneling System (SATS) could be developed. It would be a simple system designed to lower costs of tunneling in good ground with a nearly level surface. It would utilize off-the-shelf equipment and would decouple the boring and lining operations. This concept utilizes two 12-inch holes spaced 1,000 feet apart and drilled ahead of the tunneling operation. The muck would be hydraulically removed through one of these holes. The same holes would be used later to pump concrete to either a slip-forming or shotcrete machine that would line the tunnel. As the boring machine advanced, it would drop the muck on a trailing belt conveyor. The muck would be belt transported back to the last surface-service hole. The muck would be tripped off the belt, fluidized with about 15% water, and dropped into a concrete pump to be pumped through the service-hole to the surface. Compressed air would be injected into the muck-water slurry pipeline to lower the unit weight of the slurry and to decrease the viscosity of the slurry. The SATS system is described in more detail in Part IV.

II. NEED FOR PROPOSED PROJECT

No additions or modifications.

III. TECHNICAL BACKGROUND

No additions or modifications.

IV. CONCEPTS

A. Continuous Unitized Tunneling System (CUTS)

No change in description in original proposal.

B. Surface Assisted Tunneling System (SATS)

The concept for the development of a surface assisted tunneling system is shown in Figures A1 through A8. It is a good-ground system that does not, in general, require any tunnel lining for structural reasons. It is composed

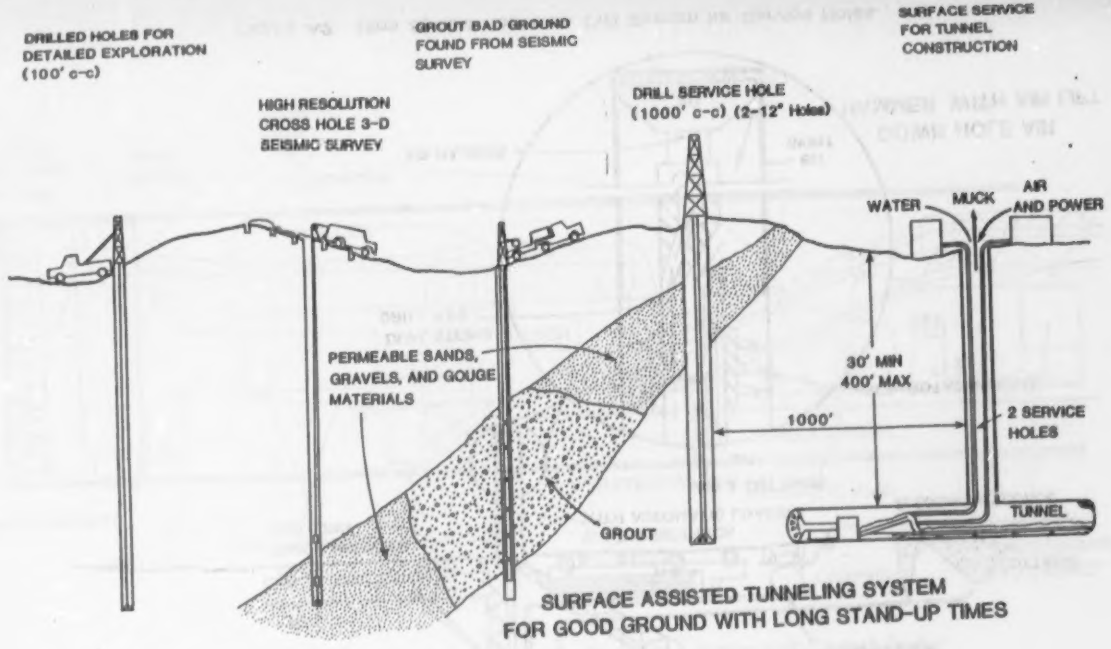

DRILLED HOLES FOR DETAILED EXPLORATION (100' c-c)
HIGH RESOLUTION CROSS HOLE 3-D SEISMIC SURVEY
GROUT BAD GROUND FOUND FROM SEISMIC SURVEY
DRILL SERVICE HOLE (1000' c-c) (2-12" Holes)
SURFACE SERVICE FOR TUNNEL CONSTRUCTION
WATER
MUCK
AIR AND POWER
PERMEABLE SANDS, GRAVELS, AND GOUGE MATERIALS
30' MIN
400' MAX
1000'
2 SERVICE HOLES
TUNNEL
GROUT
SURFACE ASSISTED TUNNELING SYSTEM
FOR GOOD GROUND WITH LONG STAND-UP TIMES

Figure A1 Drilling Scheme for Surface Assisted Tunneling System.

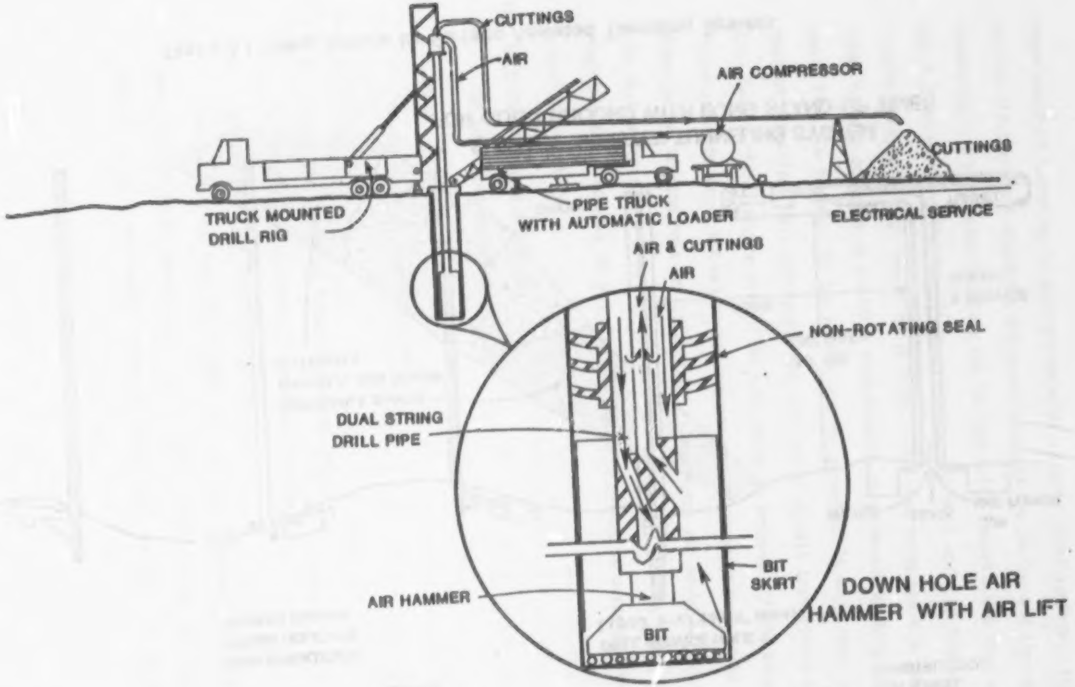

CUTTINGS
AIR
AIR COMPRESSOR
CUTTINGS
TRUCK MOUNTED
DRILL RIG
PIPE TRUCK
WITH AUTOMATIC LOADER
ELECTRICAL SERVICE
AIR & CUTTINGS
AIR
NON-ROTATING SEAL
DUAL STRING
DRILL PIPE
BIT
SKIRT
AIR HAMMER
BIT
DOWN HOLE AIR
HAMMER WITH AIR LIFT

Figure A2. High Speed Con-core Drill System for Service Holes.

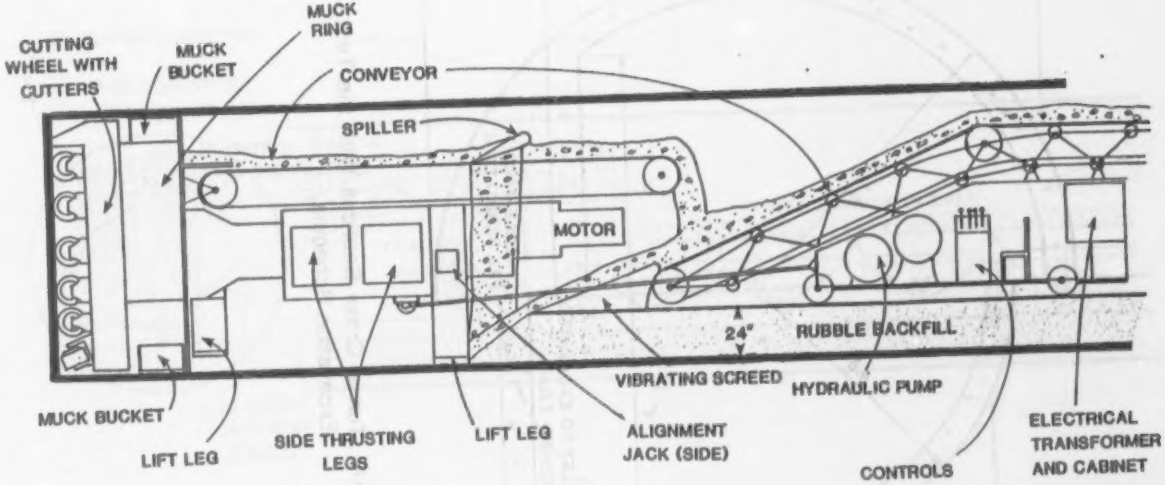

CUTTING WHEEL WITH CUTTERS
MUCK BUCKET
MUCK RING
CONVEYOR
SPILLER
MOTOR
24"
RUBBLE BACKFILL
MUCK BUCKET
LIFT LEG
SIDE THRUSTING LEGS
LIFT LEG
ALIGNMENT JACK (SIDE)
VIBRATING SCREED
HYDRAULIC PUMP
CONTROLS
ELECTRICAL TRANSFORMER AND CABINET

Figure A3. Standard Tunnel Boring in Machine with Floor Leveler and Control Trailer.

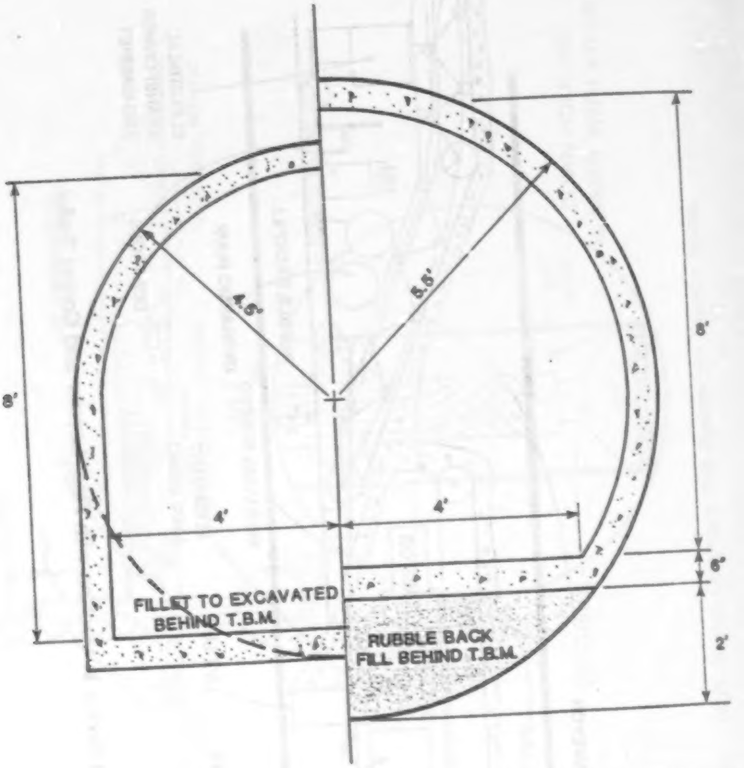

4.5'
5.5'
8'
8'
4'
4'
6"
2'
FILLET TO EXCAVATED BEHIND T.B.M.
RUBBLE BACK FILL BEHIND T.B.M.

Figure A4. Tunnel Cross Sections With the Two Different Excavation Schemes.

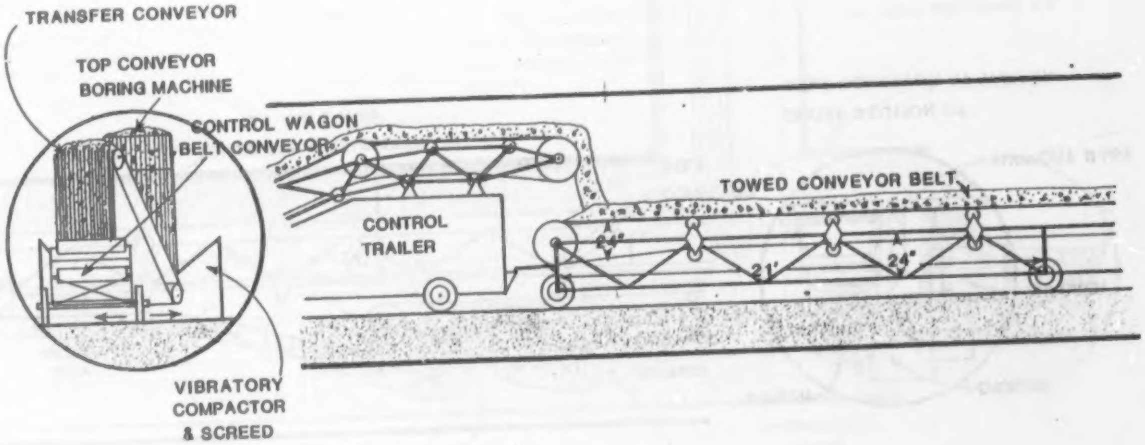

TRANSFER CONVEYOR
TOP CONVEYOR
BORING MACHINE
CONTROL WAGON
BELT CONVEYOR
CONTROL
TRAILER
TOWED CONVEYOR BELT
24"
21'
24"
VIBRATORY
COMPACTOR
& SCREED

Figure A5. Trailing Belt Conveyor.

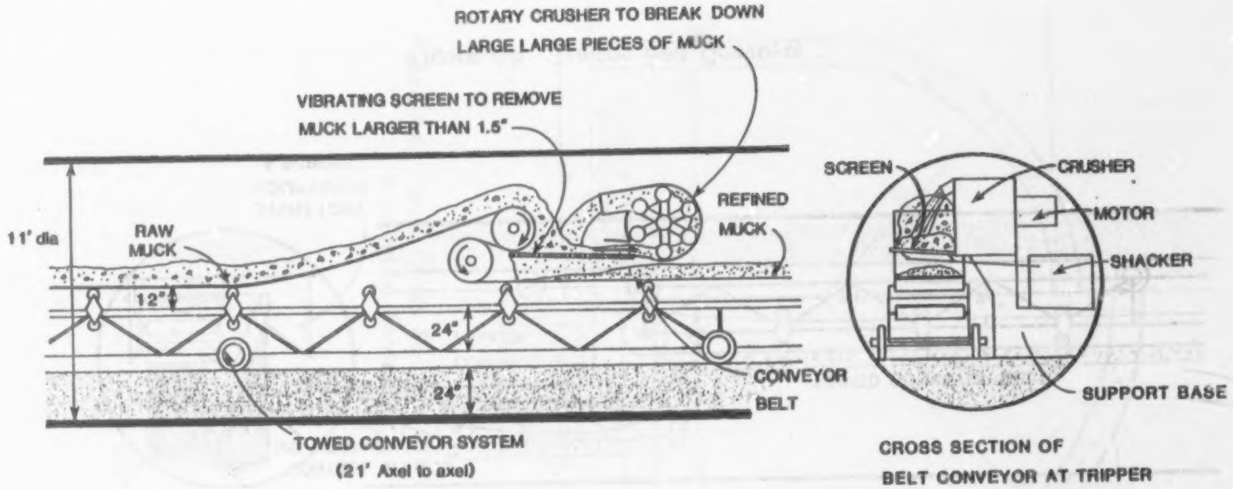

ROTARY CRUSHER TO BREAK DOWN
LARGE LARGE PIECES OF MUCK
VIBRATING SCREEN TO REMOVE
MUCK LARGER THAN 1.5"
11' dia
RAW
MUCK
12"
24"
24"
REFINED
MUCK
CONVEYOR
BELT
TOWED CONVEYOR SYSTEM
(21' Axel to axel)
SCREEN
CRUSHER
MOTOR
SHACKER
SUPPORT BASE
CROSS SECTION OF
BELT CONVEYOR AT TRIPPER

Figure A6. Tripper, Screen and Impact Crusher to Size Muck.

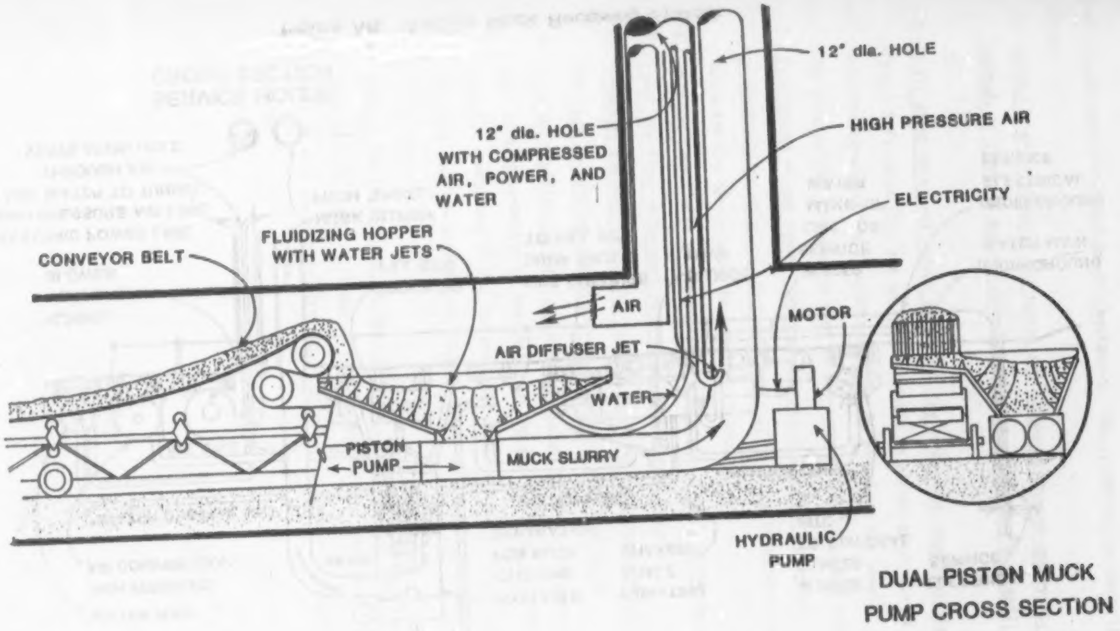

12" dia. HOLE
12" dia. HOLE WITH COMPRESSED AIR, POWER, AND WATER
HIGH PRESSURE AIR
ELECTRICITY
FLUIDIZING HOPPER WITH WATER JETS
CONVEYOR BELT
AIR
MOTOR
AIR DIFFUSER JET
WATER
PISTON PUMP
MUCK SLURRY
HYDRAULIC PUMP
DUAL PISTON MUCK PUMP CROSS SECTION

Figure A7. Tripper, Fluidizing Hopper, Concrete Pump and Air Diffuser to Lift Muck.

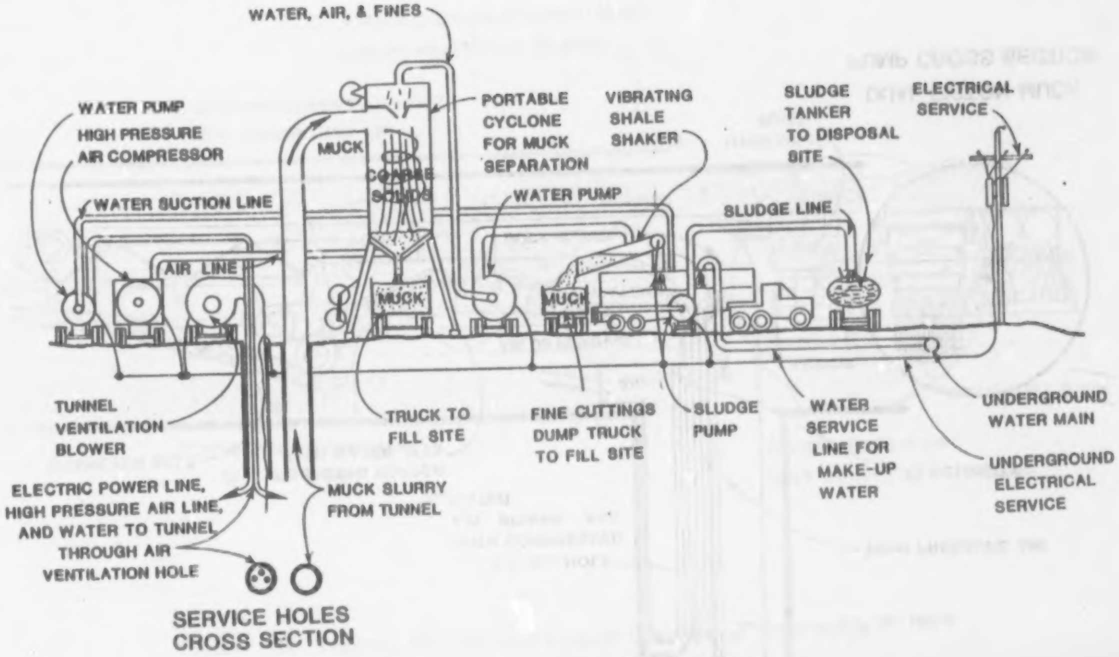

WATER, AIR, & FINES
WATER PUMP
HIGH PRESSURE AIR COMPRESSOR
WATER SUCTION LINE
AIR LINE
MUCK
COARSE SOLIDS
MUCK
PORTABLE CYCLONE FOR MUCK SEPARATION
VIBRATING SHALE SHAKER
WATER PUMP
MUCK
SLUDGE TANKER TO DISPOSAL SITE
SLUDGE LINE
ELECTRICAL SERVICE
TUNNEL VENTILATION BLOWER
TRUCK TO FILL SITE
FINE CUTTINGS DUMP TRUCK TO FILL SITE
SLUDGE PUMP
WATER SERVICE LINE FOR MAKE-UP WATER
UNDERGROUND WATER MAIN
UNDERGROUND ELECTRICAL SERVICE
ELECTRIC POWER LINE, HIGH PRESSURE AIR LINE, AND WATER TO TUNNEL THROUGH AIR VENTILATION HOLE
MUCK SLURRY FROM TUNNEL
SERVICE HOLES CROSS SECTION

Figure A8. Surface Muck Receiving System.

only of off-the-shelf, state-of-the-art equipment. The system may be summarized as follows:

1. Carefully drill ahead of the tunnel and determine through geophysical methods if there is any bad ground that requires grouting to stabilize it.
2. Drill grout holes and inject grout into the zones that need stabilization. Soft zones that are not porous enough to accept grout can be hydrofractured and the fractures injected to stabilize the zone. Jet grout-mixing can also be used in low-permeability silts and sands.
3. Drill ahead of the tunnel operation to open up two 12- to 15-inch surface service holes at about 1,000-ft spacing. The holes would be cased and the casing would be cemented if necessary.
4. Bore the tunnel with an off-the-shelf, automated tunnel boring machine.
5. Level the floor using muck to provide a level road bed.
6. Transport the muck on a 1,000-ft long, trailing belt conveyor back to the last surface service hole; remove the muck with a tripper.
7. Size and fluidize the muck and pump it to the surface. The pump will be pipe connected to the casing in the service hole. In the pipeline downstream of the concrete pump, high-pressure air will be diffused into the muck slurry through a nozzle to eject the muck to the surface.
8. Receive the muck at the surface, separate the water, and haul the muck to a fill site. It may in fact be possible to landscape the muck at each surface penetration, thus removing further transport costs.

9. Provide a surface service unit to supply ventilation air, compressed air, electric power, and water to the tunnel boring machine and the muck-removal system.
10. Provide a concrete batch plant and pumps at the surface to supply shotcrete or concrete as needed for either a shotcrete tunnel lining or a slip-formed concrete tunnel lining. This lining system is completely decoupled from the tunneling operation. The service holes used by the tunneling system would also be used by the lining system.
11. Line the tunnel with either a shotcrete robot hose supplied through the service holes, or use fast-set concrete, hose-supplied to self-propelled slip forms. Shotcrete lining would be appropriate for limestone and the concrete slip-form lining would be appropriate for either shales, clay, or sandstones.
12. Provide dual surface units for both the muck handling and the tunnel lining system so that as one unit is being moved, the other can be servicing the boring operation or the lining operation.

V. COST COMPARISON OF PROPOSED AND CONVENTIONAL TUNNELING APPROACHES

SATS should produce savings comparable to those of CUTS.

VI. RESEARCH AND DEVELOPMENT APPROACH

The discussion of industry participation should be modified as previously noted.

VII. DEFINITION OF TASKS

All CUTS work item codes should be prefixed by a "C" in Table 2.

The corresponding identification of SATS tasks is provided in Table S2 ("S" prefix distinguishes SATS tasks from CUTS tasks).

TABLE S2

SATS TASK DEFINITIONS

S1. Hole Drilling Subsystem

	Task Group	Task No.	Task Designation
S1.1.	Hole Drilling	S1.1.1.	Core Drilling
		S1.1.2.	Holes for Geophysical Exploration
		S1.1.3.	Holes for Grouting
		S1.1.4.	Service Holes for Tunneling
		S1.1.5.	Raise Boring for Access Holes
		S1.1.6.	Hole Casing
S1.2.	Detailed Subsurface Exploration	S1.2.1.	Core Analysis
		S1.2.2.	Bore Logging
		S1.2.3.	Cross Hole Geophysics
		S1.2.4.	3-D Display of Results

S2. Tunnel Boring Subsystem

	Task Group	Task No.	Task Designation
S2.1.	Tunnel Boring	S2.1.1.	Tunnel Boring Machine
		S2.1.2.	Tunnel Floor Leveling Unit

S3. Muck-Handling Subsystem

	Task Group	Task No.	Task Designation
S3.1.	Tunnel Muck Conveying	S3.1.1.	Trailing Muck Belt Conveyor
		S3.1.2.	Belt Trippers to Remove Muck
S3.2.	Muck Lift	S3.2.1.	Muck Screening & Crushing
		S3.2.2.	Muck Fluidizing
		S3.2.3.	Muck Pumping
		S3.2.4.	Muck Ejector
S3.3.	Muck Receiving & Separation	S3.3.1.	Muck Cyclones
		S3.3.2.	Water Pumps
		S3.3.3.	Shale Shaker
		S3.3.4.	Sedimentation Chamber

TABLE S2 (Cont'd.)

SATS TASK DEFINITIONS

S4. Surface Service Subsystem

	Task Group	Task No.	Task Designation
S4.1.	Surface Service Components	S4.1.1.	Portable Ventilation Blowers
		S4.1.2.	Portable Compressed Air Surface Unit for Muck Lift
		S4.1.3.	Portable Water &/or Mud Pump for Fluidizing Muck
		S4.1.4.	Portable Power Switching & Transmission Unit

S5. Concreting Subsystem

	Task Group	Task No.	Task Designation
S5.1.	Concrete Mixing & Conveying	S5.1.1.	Portable Surface Batch Plant
		S5.1.2.	Concrete Pumps
		S5.1.3.	Hose Conveyance
S5.2.	Grouting	S5.2.1.	Grout Batch Plant
		S5.2.2.	Grout Injection Pump
		S5.2.3.	Casing Cementing
S5.3.	Concrete Mix Design	S5.3.1.	Concrete Mixes for Slip Forms
		S5.3.2.	Shotcrete Mixes
		S5.3.3.	Grout Mixes
S5.4.	Slip Forming	S5.4.1.	Slip Forms & Propulsion System
		S5.4.2.	Shotcrete Robot
		S5.4.3.	Injection Pumps
S5.5.	Structural Analysis	S5.5.1.	Structural Analysis
S5.6.	Directional Control	S5.6.1.	Directional Control

VIII. DISCUSSION OF TASKS

TASK GROUP S1.1. - HOLE DRILLING

Objectives - To design a portable hole-drilling system using state-of-the-art equipment for exploration holes, grouting holes, 12-inch diameter service holes, and 36-inch diameter access holes. The equipment must be able to be set up or be taken down in a few minutes, operate with no more than two men, and drill in soft sedimentary rocks at a rate of 50 ft per hour for the small diameter holes, 20 ft per hour for the 12-inch diameter holes and 5 ft per hour for the 36-inch raise borings.

Background - Portable drilling machines have been engineered to a fairly high state, particularly the lightweight machines designed to drill no deeper than 2,000 ft. It has been well established that the rate of hole advance is primarily controlled by the rate the cuttings can be removed. Where mud is not needed to form a filter cake, air is the preferred circulation fluid. This is because of the very high velocities that can be obtained to scour the bottom of the hole and to remove cuttings.

The rate of drilling also depends on the thrust between the bit and bottom of the hole and the rotational velocity of the bit. Where heavy subassemblies cannot be added to the bottom of the drill strings to get the thrust, downhole air hammers have been found to be very efficient.

Coring is usually a very time-consuming, costly procedure because each core must be brought to the surface by withdrawing the drill string piece by piece. To take the next core, the drill string must be reentered piece by piece, and a complete trip must be made for each core. A very ingenious device has been developed to take core continuously. A dual string drill pipe is used with a diamond-core barrel on the bottom. Air is pumped down the pipe annulus to blow the cores out through the center pipe.

Hydraulic power swivels that also raise and lower hydraulically are now used to rotate the drill string. Automatic pipe elevators to position pipe to add to drill string have also been developed. These are only a few of the many advances that have been developed in the drilling industry. It is safe to say that the drilling industry is far advanced over the tunneling industry.

Planned Approach to Meeting Objectives - Walker-Neer Company of Wichita Fall, Texas and Atlas Copco, Solon, Ohio have been contacted. They have offered their advice and help for the project. These companies have some of the most advanced drilling equipment in the world. Other companies will be contacted and a system will be planned to drill swiftly the holes needed to service the tunneling operation without the costly large-shaft headworks and elevator system. The drilling scheme for the surface assisted tunneling system is shown in Figure A1. The high-speed Con-Cor drill system for drilling the service holes is shown in Figure A2. The same figure shows the downhole air hammer, the dual-string pipe, and the cuttings being removed by air.

TASK GROUP S1.2. - DETAILED SUBSURFACE EXPLORATION

Objectives - To develop a system to investigate the ground ahead of the boring machine so that the ground may be grouted or other measures taken so that the lives of workmen will not be endangered or the rate of advance slowed as the tunnel progresses.

Background - TBMs can operate in good ground that will not collapse and entrap the machine. Even though the geology indicates a site is composed of competent rocks, there is always a chance that treacherous zones have been missed. Therefore, there must be a detailed examination of the ground ahead of the machine to verify that these zones have not been missed. Where cores cannot be taken, the ground is fractured or is sand or gravel and automatically suspect. Where cores can be taken, they can be quickly broken using the Brazilian test to measure their strength. Their density and porosity can be measured and the rock can be identified.

Between holes, cross-hole shear and pressure waves can be propagated at high frequency to locate anomalies between the bore holes. The frequency of the waves and the spacing of the bore hole must be matched to locate small objects. The results of this cross-hole exploration can be correlated with the core logs and the standard downhole geophysical work used in the well industry. The final display of the result in a three-dimensional mode can be automated using the standard computer techniques used in the oil industry. This information will be used to drill grout holes and inject grout as needed before the tunneling reaches that particular location.

Planned Approach to Meeting Objectives - Sun-Sperry Company, Houston, Texas has been contacted and has given assurance of their help in selecting the proper equipment needed for this task. Other companies involved in well logging and geophysical exploration will also be contacted. These companies include Core-Lab, Dowell Schlumberger, Birdwell, and others. The well-logging and geophysical exploration industry is well advanced. The major problems will be with the high resolution required so that objects less than 1 ft thick can be located.

TASK GROUP S2.1. - TUNNEL BORING

Objectives - To select a standard Tunnel Boring Machine (TBM) that will advance 1 ft per minute (peak rates) and maintain 1,000 ft/day in soft, competent, sedimentary rock such as stiff clay, shale, chalk, and soft sandstone. The bore diameter will be from 9.5 to 11.5 ft. Disk cutter bits will be used without water-jet assistance. The machine is to be automatically directed by a system of gyrocontrols so as to maintain alignment and position within 2 inches of the required position.

Background - Tunnel boring machines have reached a good state of development; however, the muck-handling systems and the tunnel-lining systems have not kept up with TBM evolution. Usually tunnels in good rock are advanced about 85 to 100 ft per day. The record advance rate is 419 ft per day held by a Robbins machine working in Mancus shale. Machines boring upward at the Nevada Test Site have been tested at 84 ft/hour (peak rate) by the U. S. Air Force. The muck fell downward. Even then the muck-removal system clogged and limited the boring rate so that the average advance rate was only 36 ft in 8 hours. The lining system was said to have constrained the machine to this shift rate.

Planned Approach to Meeting Objectives - Both the Robbins Company of Seattle, Washington and Atlas Copco-Jarva of Solon, Ohio have been contacted. They have both offered their advice and cooperation for the project and have expressed the belief that the goals are not unrealistic if the muck removal system can be made as efficient as the present-day boring machines. Atlas Copco-Jarva has already developed a machine that spills, compacts, and levels muck to construct a level roadbed in the bottom of the cylindrical re. Figure A5 shows the difference between an 11-ft bore with the recom- ction of 2 ft of muck in the bottom to get a 9-ft wide floor, and a 9-ft re with the excavation of the two fillets below the cylinder to get a level oor. Atlas Copco-Jarva advises that the cutting element off a road header boom machine can be designed to remove the fillets in soft rock. If so, 30% excavation volume and 14% muck-transport saving can be effected. The nnel boring machine, floor leveler, and control trailer are shown in igure A3.

Figure A3 shows a standard TBM with top muck conveyor and trailer arrying the controls and transformer sled. A conveyor belt carries the ck over the control trailer. Figure A3 also shows the muck spiller, compactor, and screed to level the floor of the tunnel. Figure A4 shows the tunnel cross sections for the two different excavation schemes.

TASK GROUP S3.1. - TUNNEL MUCK CONVEYING

Objectives - To design a 1,000-ft long trailing belt conveyor that can be hitched to the TBM. The belt conveyor will carry the muck back to the surface service hole. Stationary trippers will be designed to remove the muck for sizing and transport to the surface. The peak design rate is 415 tons/hour. The conveyor will be electrically powered. Sensing elements and controls will be used to prevent overloading.

Background - One of the most efficient ways to move materials is with a conveyor belt. Such devices have been used in mines, crushing plants, etc. for years and are usually used to convey materials between two fixed points. The design of these belt conveyors using standard off-the-shelf components is well established. They have been built to convey materials for many miles.

Planned Approach to Meeting Objectives - There are several manufacturers of belt-conveyor components. One of the largest is Link-Belt. Their published information indicates a 36-inch wide belt will be required. The belt will be supported by three rollers, one horizontal and two inclined. The supporting rollers will be spaced at 48 inches. They in turn are supported by light trusses 48 inches apart and 21 ft long. If the belt is moved at 315 ft per minute, it will more than adequately carry the muck at the design rate. The ends of the support trusses will be supported by rigid frames carried on rubber tires. Each set of support trusses will be hinge-connected to the preceding and following support trusses. The trailing flexible belt conveyor will travel on the inside curve of the tunnel and occupy only one-half of the tunnel. The trailing belt conveyor is shown in Figure A5. The conventional way to remove material from a conveyor belt before the muck gets to the end

e conveyor is to use a tripper. A tripper is an "s" shaped loop of the
around two cylindrical rollers, one of which is well above the conveyor,
ther just above the plane of the conveyor. The collecting hopper is
ted under the top tripper roller and downstream from the bottom tripper
er. Often trippers are moveable and carried by the conveyor support
ses for the purpose of filling several storage hoppers uniformly. In
application the reverse will be true. The belt conveyor will move along
the TBM past the stationary tripper at the surface service holes. In
ition to Link-Belt, other manufacturers of belt conveyors will be contacted
determine the best and most practical design.

TASK GROUP S3.2. - MUCK LIFT

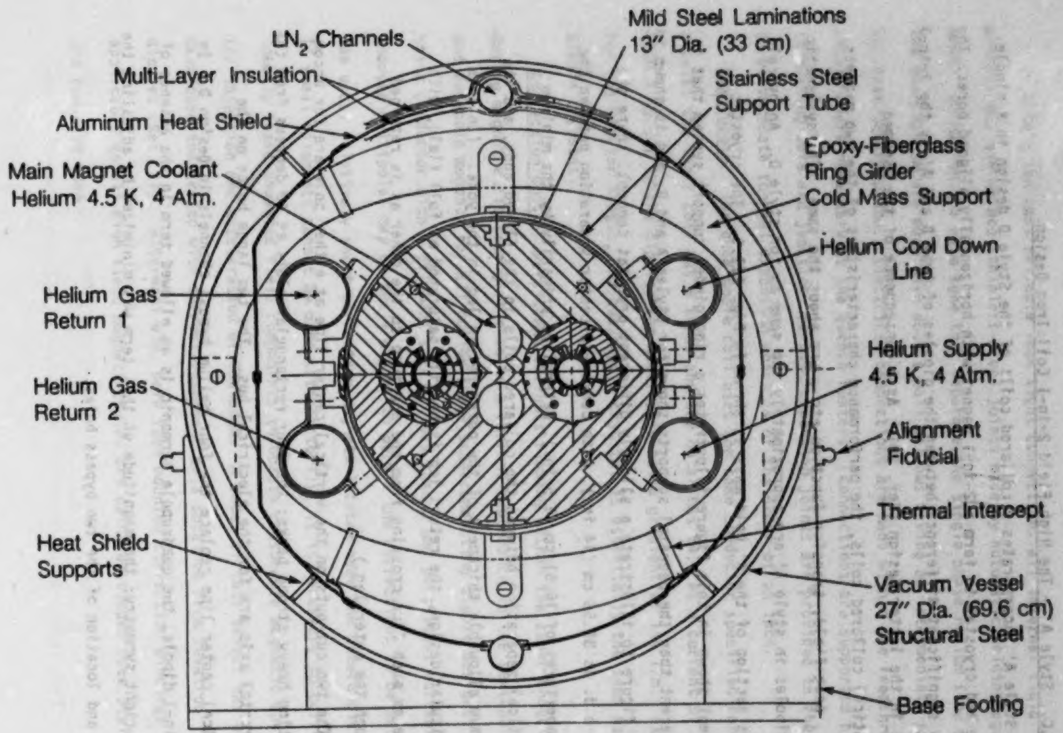
Objectives - To design a system to remove the muck from the trailing conveyor and eject it up through the lightly cased 12-inch service holes to the surface. The design rate is 415 tons per hour and the maximum lift is 400 ft, with the minimum lift 40 ft.

Background - Concrete pumps have been used to pump-lift concrete 1,035 ft at a rate of 75 cu yds per hour. They have also been used to pump concrete horizontally over 3,500 ft in light-gage steel pipe. Therefore, if the muck can be crushed to a maximum particle size of 1½ inches and if at least 15% water added, it can be efficiently pumped to the surface. This will eliminate many of the problems associated with mechanical elevator, large shafts, or bucket conveyors. An air lift would be even better, but there are space problems in designing the equipment to fit into one-half the tunnel so that the trailing conveyor can pass by.

The muck can be tripped off the conveyor belt, passed over a sizing screen, and the oversize material sent through a conventional, off-the-shelf impact crusher. The screen and crusher are only a backup to prevent clogging of the concrete pump, for if the disk cutters are changed regularly and spaced properly, all muck should be 1½ inches or smaller.

Water can be added to muck in a fluidizing hopper. Water is jetted through the sides of the tank to separate the muck pieces so that it will speedily fall into the concrete piston pump. The concrete pump will be attached to a pipeline temporarily attached to the casing in one of the surface service holes. Downstream of the concrete pump a high pressure air nozzle diffuser will inject air into the muck slurry to lower its specific gravity and its viscosity. Steam may be a more effective medium to inject into the muck and lower the head on the concrete pump. Air lift diffusers are a common method of ejecting cuttings in the oilfield industry. They are used above and below the water table and with mud drilling fluids to great depths.

Planned Approach to Meeting Objectives - Schwing Company, White Bear, Minnesota, that manufactures concrete pumps, and Shotcrete Plus Inc., Euless, Texas have been contacted and the muck pumping discussed at length. They have offered their help and assistance. Eimco, Challenge, Toyo, Hercules, and other manufacturers of pump equipment have also been contacted. Halliburton Company, heavily involved with cementing of oil wells, has volunteered their help. Other manufacturers will also be contacted and the best combination of off-the-shelf equipment selected to optimize the system. The tripper, screen, and impact crusher are shown in Figure A6. The tripper, fluidizing hopper, concrete pump, and air injector are shown in Figure A7.



LN$_2$ Channels
Multi-Layer Insulation
Aluminum Heat Shield
Main Magnet Coolant Helium 4.5 K, 4 Atm.
Helium Gas Return 1
Helium Gas Return 2
Heat Shield Supports
Mild Steel Laminations 13" Dia. (33 cm)
Stainless Steel Support Tube
Epoxy-Fiberglass Ring Girder Cold Mass Support
Helium Cool Down Line
Helium Supply 4.5 K, 4 Atm.
Alignment Fiducial
Thermal Intercept
Vacuum Vessel 27" Dia. (69.6 cm) Structural Steel
Base Footing

Fig. III.6 Magnet style A helium containment cross section.

III.D. Style C - Superferric Magnet Option for the SSC

The basic superferric idea for the SSC started at Snowmass in the summer of 1982. A concentrated effort began in March of 1984 when the Texas Accelerator Center was formed.

As currently conceived (Ref. 8), the main ring of the SSC would be made up of 1330-115 meter units, plus the necessary straight sections and interaction regions, and have a total circumference of 162 kilometers. Each of the 115 meter units would be made up internally with three 35 meter dipoles, a 4.7 meter quadrupole, and a 4.3 meter spool piece containing correction elements, position monitors, expansion joints, and heat exchangers. It is proposed that the 35 m unit dipoles, quadrupoles, and spool pieces would be assembled individually at various industries throughout the country. These units would be shipped to the SSC site and assembled above ground into a single 115 meter unit. Externally this would be a 16-3/4 in. diameter pipe serving as the vacuum chamber for the full unit. The insulating vacuum would be pumped and then sealed off. These units would then be inserted into the main tunnel at four locations and welded together to make up the arcs of the accelerator. The magnets would be transported by a specially made self-propelled vehicle that could follow a guide wire located in the floor.

Magnet design. Figure III.7 is a cross section of the 3 T superferric magnet. The magnet has three independent windings: I_1 are the four turns closest to the horizontal plane, I_2 are the four turns farthest from the horizontal plane,and I_3 is the trim coil on the edges of the pole face. The main dipole field is set by the sum of the three currents, $I_1+I_2+I_3$; the systematic b_2 (sextupole) is adjusted to zero by the ratio I_1 to I_2, and the systematic b_4 (decapole) is adjusted to zero by I_3. The systematic b_6 multipole is the first nonzero coeffecient for this design. Its

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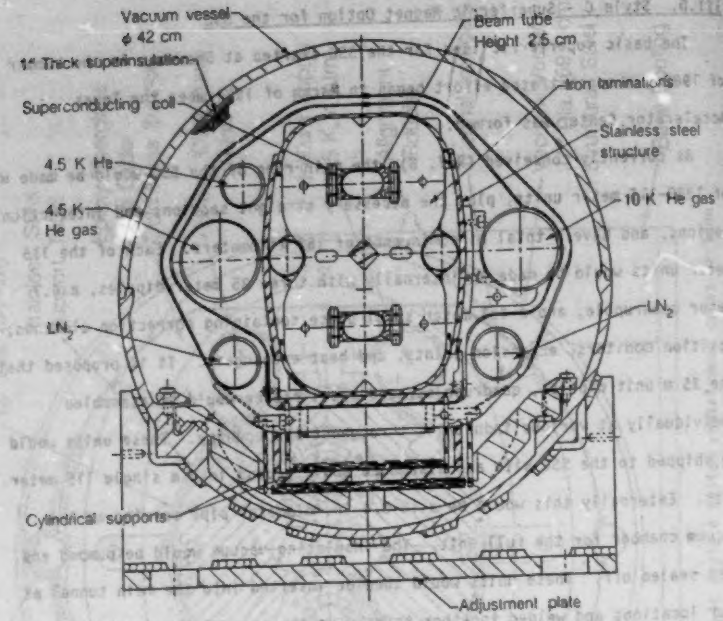
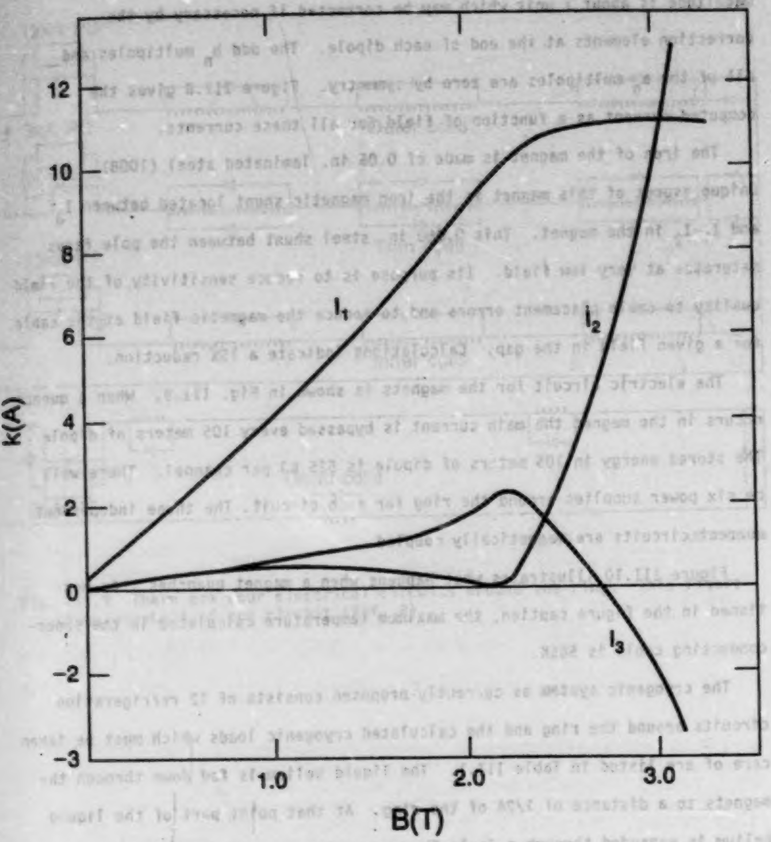

Vacuum vessel
ϕ 42 cm
Beam tube
Height 2.5 cm
1" Thick superinsulation
Iron laminations
Superconducting coil
Stainless steel structure
4.5 K He
4.5 K He gas
10 K He gas
LN$_2$
LN$_2$
Cylindrical supports
Adjustment plate

Fig. III.7 The 2-in-1 3 Tesla superferric magnet is enclosed in a vacuum chamber of 16-3/4 in. o.d. The iron is 1/16 in. laminations. The two magnet channels are magnetically independent. The vertical gap of the magnet is 1 in. and the calculated good field is greater than 2 cm diameter. The support in the figure is made of two concentric fiber glass cones, one between 10K and 80K and the other between 80K and 300K. There is a support every 24 feet. The small pipes are for liquid helium and nitrogen and the larger ones for helium gas. Sixty layers of superinsulation are between 80K and 300K (From Ref. 8).



XBL 857-11227

Fig. III.8 The calculated values of the three independent currents as a function of magnetic field (Ref. 8).

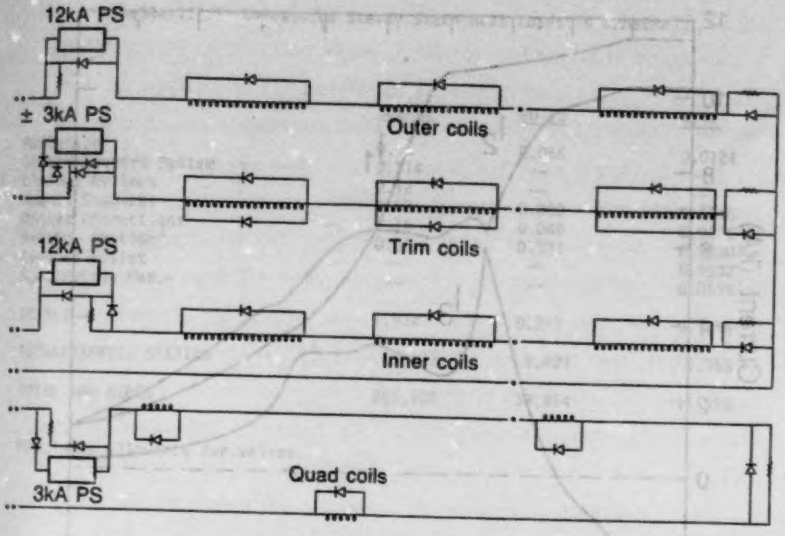
magnitude is about 1 unit which may be corrected if necessary by the correction elements at the end of each dipole. The odd b_n multipoles and all of the a_n multipoles are zero by symmetry. Figure III.8 gives the computed current as a function of field for all these currents.

The iron of the magnet is made of 0.06 in. laminated steel (1008). A unique aspect of this magnet is the iron magnetic shunt located between I_3 and I_1-I_2 in the magnet. This 0.060 in. steel shunt between the pole faces saturates at very low field. Its purpose is to reduce sensitivity of the field quality to cable placement errors and to reduce the magnetic field at the cable for a given field in the gap. Calculations indicate a 15% reduction.

The electric circuit for the magnets is shown in Fig. III.9. When a quench occurs in the magnet the main current is bypassed every 105 meters of dipole. The stored energy in 105 meters of dipole is 525 kJ per channel. There will be six power supplies around the ring for each circuit. The three independent current circuits are magnetically coupled.

Figure III.10 illustrates what happens when a magnet quenches. As mentioned in the figure caption, the maximum temperature calculated in the superconducting cable is 565K.

The cryogenic system as currently proposed consists of 12 refrigeration circuits around the ring and the calculated cryogenic loads which must be taken care of are listed in Table III.1. The liquid helium is fed down through the magnets to a distance of 1/24 of the ring. At that point part of the liquid helium is expanded through a Joule Thompson valve to cool it giving a two phase helium, and the other part of the liquid is returned in a separate pipe. Between every cell, that is, every 230 meters, there is a heat exchanger where the returned and cold gas are combined to heat exchange with the helium coming down through the magnets. In this manner, the full length of magnets is kept


12kA PS
± 3kA PS
12kA PS
3kA PS
Outer coils
Trim coils
Inner coils
Quad coils

XBL 857-11232

Fig. III.9 There are four electrical circuits around the ring. This figure shows one-half of one circuit (Ref. 8).

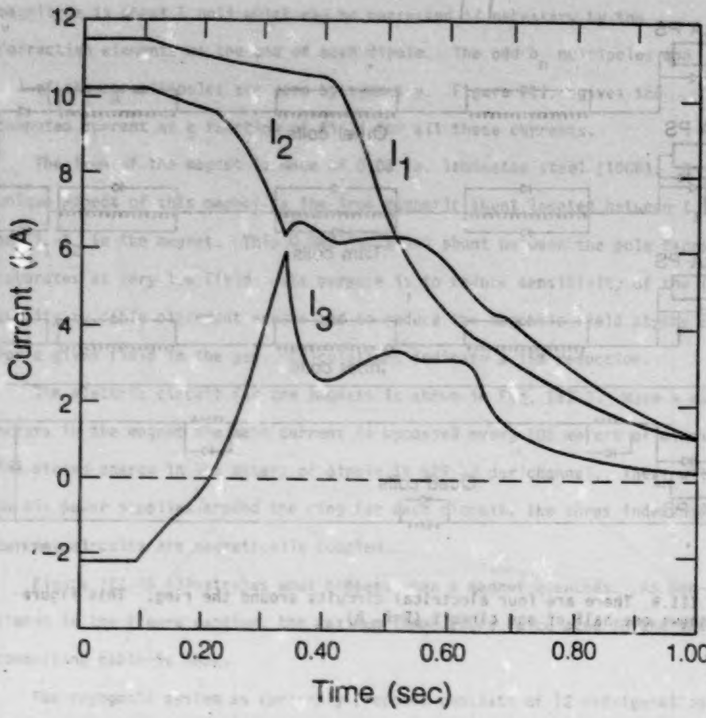


Fig. III.10 Model calculations of currents during a quench. The quench that produces the highest temperature in any conductor occurs at full current and in I_2 (shown). Normally quenches will occur by beam loss in I_1. The quench occurs at t=0.0, and in this model the power supply is removed at t=0.1 seconds. The diode in in circuit I_2 begins to bypass current at t=0.2 seconds (fires at 4 V). The trim current I_3 diode fires at t=0.2 seconds and the whole I_3 circuit quenches at t=0.3 seconds. The diode in circuit I_2 fires at t=0.4. Calculations indicate that the wermest spot in I_1 is 565K, in I_2 472K and in I_3 40K (Ref. 8).

Table III.1 Calculated Steady State Heat Loads in W/Meter.

	300-80	80-10	4.5K
Radiation	0.75	0.066	0.0124
Shield Support System	0.114	—	—
Closure Bellows	0.12	—	—
Magnet Supports	0.63	0.080	0.0040
Magnet Connections	0.16	0.040	0.0200
Refrig. Station[a]	0.06	0.031	0.0800
Contact Resist	—	—	0.0032
Synchrotron rad.	—	—	0.0579
TOTALS	1.834	0.217	0.1055
TOTAL/REFRIG. STATION	23,842	2,822	1,366
TOTAL FOR RINGS	286,100	33,864	16,396

[a] Includes allowance for valves.

cool. A shield will be at a temperature of about 10K. When a quench occurs, the warm helium in that magnet or magnets is removed at the next spool piece where there are cryogenic valves that allow this warm helium to be put into the return lines.

III.E. Style C* - 1-in-1 Superferric Magnet Option for the SSC

The design of the 1-in-1 superferric magnet option is derived from the 2-in-1 Design C. Only differences in the design will be presented in this section. Figure III.11 is a cross section of the magnet.

The magnetic and electrical properties are identical to the 2-in-1 magnet. The principal problem is to support the magnet. We have used a double fiber glass epoxy support similar to the 2-in-1 design. The thickness of the cylinders is one-half that of the 2-in-1; however, there are twice as many, so the conductive heat leak is approximately the same. The moment of inertia of the structure has been increased by adding the beam structure on the bottom of the magnet. It has been shaped to give maximum moment of inertia and to allow placement of necessary cryogenic lines. The diameter of the vacuum vessel is 12 in. compared to 16-3/4 in. for the 2-in-1. Thus the total surface area is 1.4 times the 2-in-1. The number of independent end boxes is twice the 2-in-1. The total cryogenic load is estimated to be 1.4 times the 2-in-1.

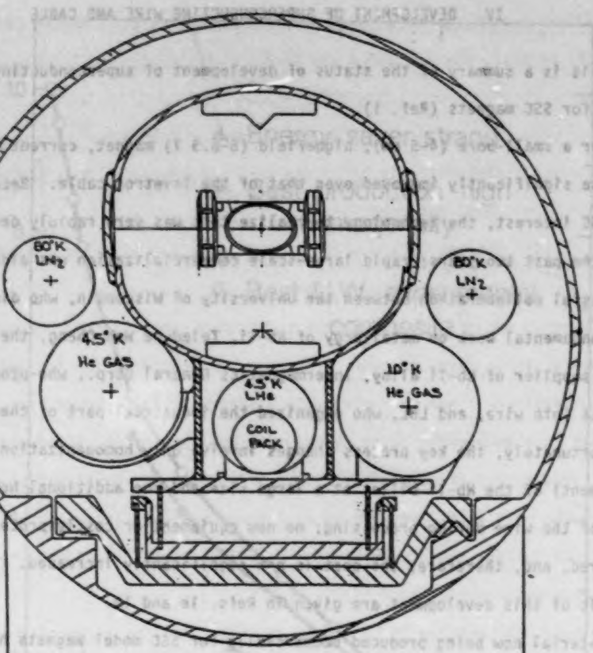

80°K
LN2
80°K
LN2
4.5°K
He GAS
10°K
He GAS
4.5°K
LHe
COIL
PACK

Fig. III.11 Superferric style C* 1-in-1 magnet.

IV. DEVELOPMENT OF SUPERCONDUCTING WIRE AND CABLE

This is a summary of the status of development of superconducting wire and cable for SSC magnets (Ref. 1).

For a small-bore (4-5 cm), high-field (6-6.5 T) magnet, current density must be significantly improved over that of the Tevatron cable. Because of the SSC interest, the technology to realize this was very rapidly developed over the past two years; rapid large-scale commercialization was aided by a successful collaboration between the University of Wisconsin, who did much of the fundamental work on metallurgy of Nb-Ti, Teledyne Wah Chang, the major world supplier of Nb-Ti alloy, Intermagnetics General Corp., who processed billets into wire, and LBL, who organized the industrial part of the effort.

Fortunately, the key process changes involve only homogenization (via heat treatment) of the Nb-Ti billet at a large size and one additional heat treatment of the wire during processing; no new equipment or costly process is required, and, therefore, the cost is not significantly increased. The details of this development are given in Refs. 1e and 18.

Material now being produced commercially for SSC model magnets has current density between 2500 A/mm^{2*} and 2700 A/mm^{2*} depending on strand size. Improved heat treatments produce at least 3000 A/mm^{2*} in laboratory pilot tests; thus, further improvements are expected in production. Figure IV.1 shows J_c vs. field for several Nb-Ti composites.

For reference, the Tevatron specification was 1800 A/mm^2. For the Reference Designs, an anticipated J_c of 2400 A/mm^2 was assumed; this has now been exceeded. The most recent Design D model magnets** use material with 2500 A/mm^2 in layer 1 and 2650 A/mm^2 in layer 2, and reach 6.6 Tesla.

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*A/mm^2 at 5 T, 4.2K, for an equivalent resistivity of 10^{-12} ohm-cm.
**4.5 m models at BNL and 1 m models at LBL.

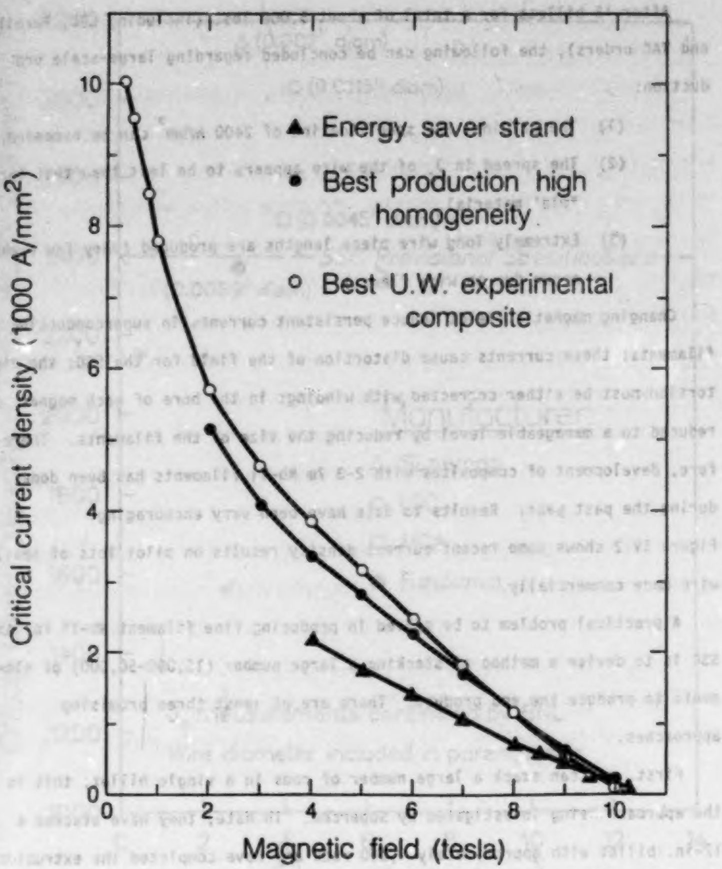

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Fig. IV.1 Progress in raising the J_c of Nb-Ti.

After 15 billets for a total of about 5,000 lbs. (including LBL, Fermilab, and TAC orders), the following can be concluded regarding large-scale production:

(1) The original SSC specification of 2400 A/mm^2 can be exceeded.

(2) The spread in J_c of the wire appears to be less than that for "old" material.

(3) Extremely long wire piece lengths are produced (very few breaks occur due to wire flaws.)

Changing magnetic fields induce persistent currents in superconducting filaments; these currents cause distortion of the field for the SSC; the distortion must be either corrected with windings in the bore of each magnet, or reduced to a manageable level by reducing the size of the filaments. Therefore, development of composites with 2-3 ?m Nb-Ti filaments has been done during the past year. Results to date have been very encouraging. Figure IV.2 shows some recent current density results on pilot lots of small wire made commercially.

A practical problem to be solved in producing fine filament Nb-Ti for the SSC is to devise a method of stacking a large number (15,000-50,000) of elements to produce the end product. There are at least three promising approaches.

First, one can stack a large number of rods in a single billet; this is the approach being investigated by Supercon. To date, they have stacked a 12-in. billet with approximately 4,000 rods and have completed the extrusion successfully. The second phase will consist of another 12 in. diameter billet with a 1.8:1 Cu:SC ratio and a filament number yet to be specified. A third phase billet would contain approximately 40,000 filaments and yield a final filament size of 2 ?m.

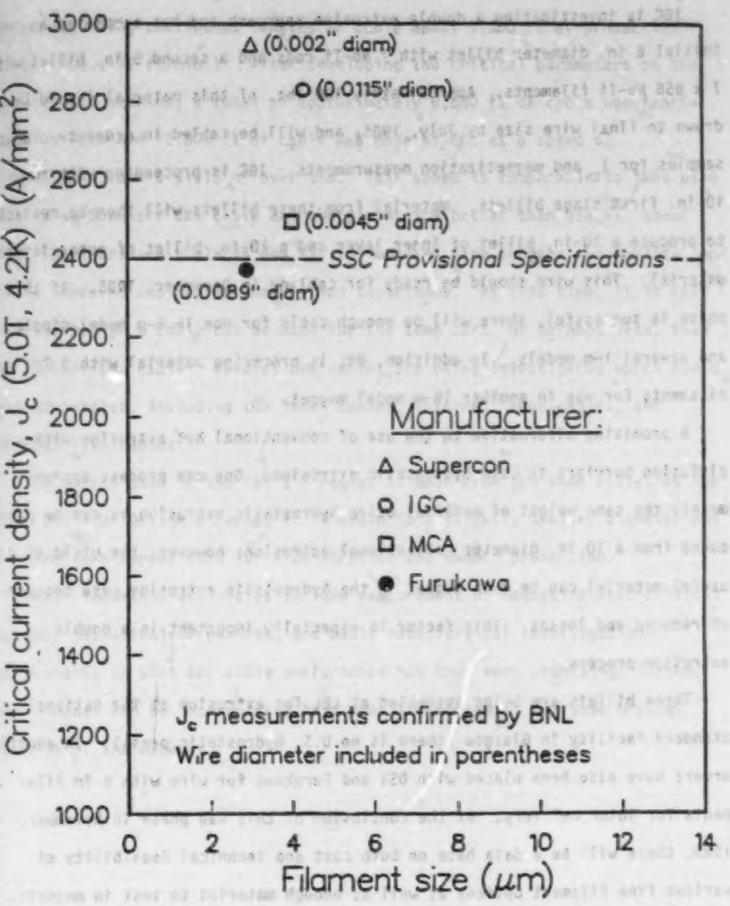

Fig. IV.2 Recent fine filament Nb-Ti results.

IGC is investigating a double extrusion approach and has completed an initial 6 in. diameter billet with 7 Nb-Ti rods and a second 6 in. billet with 7 x 858 Nb-Ti filaments. Approximately 100 lbs. of this material should be drawn to final wire size by July, 1985, and will be cabled in order to produce samples for I_c and magnetization measurements. IGC is proceeding with two 10-in. first stage billets. Material from these billets will then be restacked to produce a 10-in. billet of inner layer and a 10-in. billet of outer layer material. This wire should be ready for cabling in December, 1985. If this phase is successful, there will be enough cable for one 16.6-m model dipole and several 1-m models. In addition, BNL is procuring material with 5 ?m filaments for use in another 16-m model magnet.

A promising alternative to the use of conventional hot extrusion with diffusion barriers is cold hydrostatic extrusion. One can process approximately the same weight of material using hydrostatic extrusion as can be produced from a 10 in. diameter conventional extrusion; however, the yield of useful material can be much higher in the hydrostatic extrusion case because of reduced end losses. This factor is especially important in a double extrusion process.

Three billets are being assembled at LBL for extrusion at the National Standard Facility in Glasgow (there is no U.S. hydrostatic press). In addition orders have also been placed with OST and Furukawa for wire with 5 ?m filaments for later delivery. At the conclusion of this R&D phase in November, 1985, there will be a data base on both cost and technical feasibility of various fine filament options as well as enough material to test in magnets.

Cable development has been proceeding along two paths-cabling experiments at LBL and process improvements at NEEW (New England Electric Wire Co., the sole U.S. supplier of this service). An experimental cabling machine at LBL can produce long continuous lengths of cable about 5,000 ft at production speeds (e.g., 12 ft/min.). After developing the critical parameters on the experimental machine, a total of approximately 8,000 ft of cable was fabricated at NEEW and 12,000 ft of cable was made at LBL at a speed of 10-12 ft/min. and a yield of over 95Δ. This speed is comparable to that used at NEEW on Doubler/ CBA cable and the yields are better than 95Δ vs. about 80Δ. The increased yield is due (1) to improved wire lengths and quality, and (2) to improved cabling parameters and techniques. At this time, it is felt that the Design D cable can be made for the same cost, or perhaps less, than the Doubler/CBA cable. Several new cables are being investigated which could have advantages, including two level cables, internal wedge cables, and internal flat cables.

The strand used in the TAC 3 T magnet is made from the same billet as the inner cable of Design D except it is drawn to a slightly smaller diameter and soldered to a copper core for stabilization and quench protection.

Other important activities include measurement of magnetization, critical current, mechanical properties, and basic metallurgical investigations. Improvements in wire and cable performance has been very promising; further improvements can be incorporated into the SSC program at any time without redesign of the magnets.

V. R&D PROGRAM

V.A. Introduction

This section will discuss the program necessary to bring each magnet style up to the "preproduction stage." We define this stage to mean:

1. A detailed design and set of specifications exist for the magnet.
2. Enough models have been constructed and tested so that there is a reasonable expectation that the magnet in No. 1 can be built.
3. There has been enough R&D effort on manufacturability so that the magnet described in No. 1 can be mass produced at minimum cost using techniques that either exist or can be developed in the industrial environment.

We do not address here the selection of which style magnet should be chosen for the SSC as that is outside the scope of our charge. Rather we try and outline the program that will have to be implemented once the choice has been made.

Following the style choice, the next most important decisions are the size of the aperture and the machine lattice. At this point a detailed design of the machine will start to evolve, and R&D past and future will be used during this design evolution to create a magnet with acceptable cost that will function in the SSC in a highly reliable manner. In particular, the R&D program will be directed toward making comparisons between various alternatives and fixing parameters in a cost-effective way. Thus, for example, a general model for errors in superconducting magnets will no longer be of interest, but only a model for errors generated by a specific proposed fabrication procedure.

The data base we have at present varies with the style, and it is for this reason that R&D programs shown below for the different styles differ; however, the position of the committee is that sufficient data exist to make a style choice now, and the most economical path for the future will be to concentrate the R&D on the particular engineering problems that are associated with developing a specific magnet for the SSC.

The problem of gas desorption by synchrotron radiation affects the development program of all the magnets in that a bore tube liner may be required within the magnetic aperture. The necessary R&D to evaluate the seriousness of this problem has not been done. Basic coefficients for photodesorption of molecules from cold surfaces as a function of photon energy and incident angle of synchrotron radiation have not yet been measured. However, an experiment at the NSLS is underway and will give a preliminary measure of the magnitude of the effect by August, 1985. From this early experiment, it should be possible to estimate whether liners in the bore tube are necessary.

Following the early experiments, more refined experiments to measure the effect of the radiation on the final bore tube surface will hopefully be conducted. Since the overall magnitude of the problem is uncertain by many powers of ten, it is premature to speculate on the significance of the factor of two difference in radiated power in a low-field versus a high-field magnet system.

In summary, this problem should not be viewed as a threat to the viability of the SSC. The solution to the problem is to install a bore tube liner. The impact of this decision is that more magnet aperture may be required. This is another example of where the engineering R&D will be most economically used if it is directed at solving the problem specifically for the magnet style to be used.

A few general comments on the R&D program after style selection are in order. First, the work on spool pieces and quadrupoles is not very advanced for any style magnet, although a great deal of generic information is available from the Tevatron. Much work remains to be done on these components, and it is very specific to magnet style and machine lattice. Funding is badly needed to allow the design of these components to proceed in a timely manner after the style is fixed. There will be enough trained personnel within the magnet centers to undertake this program if funds are available.

A second point concerns the time delay in the program if a decision is made to change the size of the aperture of the magnet from that presently being produced. It was generally agreed by the committee that such a change will result in an additional 9-12 months delay before modified magnets become available for test. Tooling must be changed, many calculations redone, and the "component supply lines" refilled with different size components. If an aperture change is made, one could anticipate that the present size magnets would continue to be produced and appropriate measurements made using them until the modified magnets are brought into production. Experience with such a scenario occurred when BNL, FNAL, and LBL decided to concentrate their collective efforts on the D style 4 cm aperture magnet. In what follows, we break the magnets into two different categories: (1) cos θ and (2) superferric. Since all of the cos θ magnets use collared coils; they have many similarities and a few differences.

1. Type D; 1-in-1; high field, cold Fe.
2. Type B; 1-in-1; high field, no Fe.
3. Type A; 2-in-1; high field, cold Fe magnetically coupled apertures.

Type D is discussed in detail first and the other two treated as perturbations. It was estimated that switching from D to type A would add six months to the program due to the additional studies required because of the magnetic coupling between apertures.

1. Type C; 2-in-1; low field; cold Fe; no magnetic coupling.
2. Type C*; 1-in-1; low field; cold Fe.

In this case the major design effort has been concentrated on the type C although models of C* were used in early tests of this style magnet.

An explanation of the remaining part of the section is in order. The presentations given are those of the "proponents" for the various style magnets. The time schedule is only for purposes of illustration, and it should be noted that all of the resources of the community are expected to become available for a concentrated program after the choice of style has been made. The schedules shown do not reflect this fact, and the committee did not feel it was in the scope of its charge to focus on how the resources will be deployed in the future.

In our Texas meeting, we considered each design and tried to establish the extent of the necessary R&D to bring it to the preproduction prototype level. Each magnet design was graded as to the status of its development relative to each of the following areas:

1. Stress Analysis
    - a. Collars or magnet yoke in superferric case.
    - b. Cryostat support system
        1. Mechanical loading
        2. Shipping loads
        3. Thermal induced stress
2. Electrical System Performance Analysis
    - a. Electrical insulation
    - b. Transients during quench and excitation of magnets
    - c. Regulation of currents if more than one circuit is involved.

3. Vacuum System Performance Analysis
   a. Bore tube vacuum studies
   b. Synchrotron light gas desorption
   c. Insulating vacuum
4. Cryogenic System Performance Analysis
   a. Adequate conductor cooling
   b. Synchrotron radiation heat removal
   c. Initial cooldown
   d. Behavior under quench, maximum pressure, recovery time.
5. Quench Behavior
   a. Maximum temperature in coil package
   b. Active or passive system suitable
   c. Voltages induced during quench
   d. Quench detection system
6. Bore Tube Plating Feasibility
7. Interconnections Design
   a. Mechanical
   b. Electrical
8. Model Tests for Future R&D
   a. Training
   b. Field level
   c. Systematic errors
   d. Random errors
   e. Quench heating
   f. Alignment and support
9. Status of Production Engineering Design
   a. Manufacturing plan
   b. Development of tooling
10. Design Review
    a. Internal
    b. External
11. Correction Coil Design
    a. Lumped
    b. Distributed
12. Current Lead Design
13. Status of Production Testing Instrumentation
14. Maintenance and Replacement Considerations

The problem involving synchrotron radiation gas desorption affects all the designs and has been split off and described above. It is to be viewed as possibly requiring an increase in aperture with the consequent delay mentioned above.

For each of the styles the three most significant engineering R&D areas were identified. In addition there were ten to twelve areas identified that would require continuing effort and that affected either the magnet itself or the magnet as installed in a system. Some of these issues were common to all designs, and some were design specific. The committee tried to come to a consensus and give a quantitative estimate of how much work remained in each area for each magnet design, but unfortunately, although as a committee we could agree on the areas requiring attention, it was apparent that there was no possibility of reaching agreement on how much engineering R&D remained or the contingency that should be assigned to cover any remaining uncertainty.

As a result, at the end of our TAC meeting, each "proponent" was asked to respond in writing about how he would direct the R&D in those areas that were brought into question. At our final meeting at BNL, we took those responses as the basis of the required R&D program--the three most significant areas are broken out and discussed explicitly, and the continuing engineering R&D tasks are listed in table form. The written responses are also included and give more complete information than the Tables V.1 and V.2.

The panel was thus not able to respond to its charge of providing an "estimate of the time and manpower needed to complete the preproduction R&D." The estimates in the following sections are those of the "proponents" and should only be viewed as indicating a plausible scenario in the eyes of the proponents. The contingency that should be applied to these programs is obviously very different due to the fact that much more experience exists with the cos θ style magnets as used in the Tevatron, than with any of the others. The key issue of assigning a rational contingency to the other designs must take place in a broader forum than one just restricted to magnet technology which is the case for this committee. Invariably in debating this issue the committee would get involved in questions concerning SSC machine lattice or aperture, machine operation, or total project cost--all of which were areas outside the charge, but clearly have a strong bearing on the future magnet development program. With this preamble we go on to the proponents' R&D programs.

V.B. Cos θ Style Magnet R&D Program (BNL, FNAL, LBL Response)

BNL, FNAL, and LBL working together in a collaborative effort have, since January, 1985, emphasized Design D as the most effective approach to the resolution of major R&D issues for all of the high-field cos θ designs. In fact, we believe that all of the key issues involved in the demonstration of a successful cos θ design have been identified and are either resolved or will be resolved by the end of FY85. We further contend that by this time, as a result of the successful 1 meter dipole program at LBL (8 magnets), the 4.5 meter program at BNL (6 magnets), the already completed cryostat development work at FNAL, and the superconductor wire development at LBL, the University of Wisconsin and in industry, we will have demonstrated by model tests all of the critical features of Design D. In addition, we will have accumulated a sufficient data base to begin an aggressive program leading up to the production in the laboratories and in industry of prototype models of the SSC dipole magnets in FY87 in accordance with existing manufacturing plans and production approaches which have been successfully demonstrated.

This program of solid accomplishment coupled with the base of knowledge and experience achieved through the design, construction, and operation of the Tevatron along with the demonstration of manufacturability of high-field cos θ magnets at Fermilab, BNL, LBL, Europe, Japan and the Soviet Union establishes the data base for an in-depth assessment of the technical status of the D style magnet. Following the completion of this FY85 effort, the final confirmation of the Design D systems approach will occur during the preliminary string test of a half cell at FNAL in about one year. With these results, the laboratory and industrial prototype magnets fabrication experience and the incorporation of cost optimization features to be developed in FY86 and FY87, fabrication of initial production magnets can begin in FY88.

With regard to funding and resources, the technical data discussed below under item 1 will, in the main, be completed this fiscal year without additional funds. Assuming FNAL, BNL, and LBL receive the same funding in FY86 as they have in FY85, the half cell preliminary string test can be completed with existing personnel resources shown in Fig. V.1. With additional funding, personnel resources exist to develop more, such as quadrupole and spool piece design and modeling, cost optimization R&D and industrial involvement. A possible schedule is included in the Appendix.

Finally, should Design A or B be chosen, the overall cos θ program would be delayed three to six months due to tooling changes and if the aperture were changed the delay would be nine to twelve months. Additional R&D is addressed below.

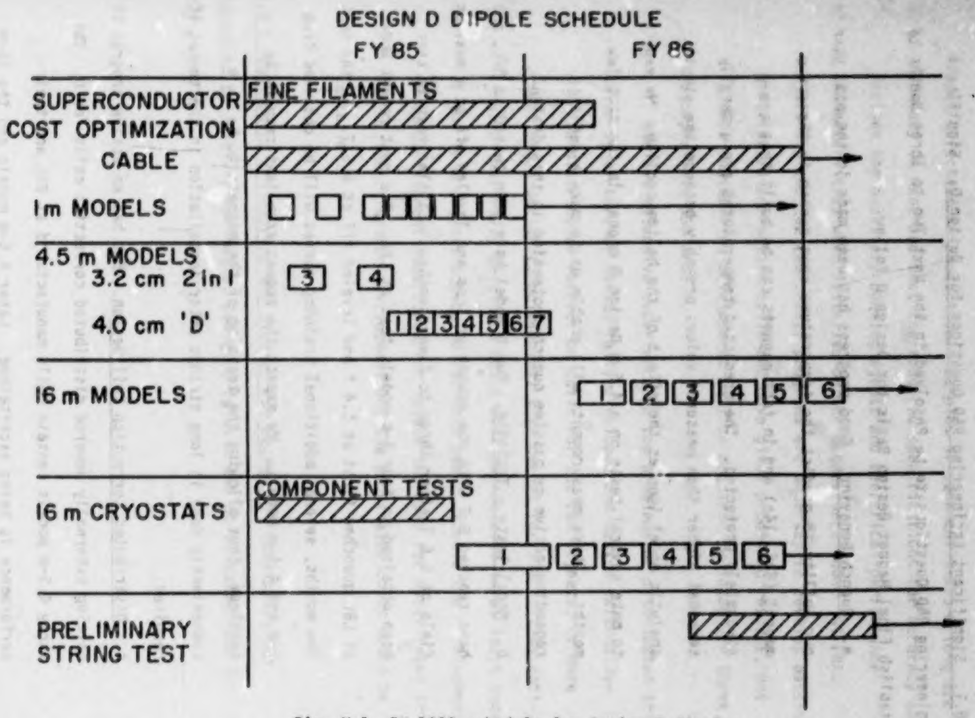

Fig. V.1 FY 1986 schedule for Design D dipoles.

V.B.1. Significant Engineering R&D Questions for Design D. Significant Engineering R&D Questions to be Resolved in the Next Two to Three Months to Establish Final Magnet Design Basis for Design D follow.

a. Quench Behavior. Good progress has been made in the past year in our ability to predict the temperature upon quench in the cos θ magnet (Ref. 14a) and in fact magnets can be built that are adequately protected. The predicted temperatures are generally somewhat higher than measured values probably because the simple analytic model ignores the effect of the helium cooling. We expect to make several tests on a 4.5 m Design D magnet in the next few months. These measurements will enable us to make a decision regarding active or passive quench protection in this design.

b. Model Tests - Training. Two D model have been tested at BNL, and have reached 6 T with one quench or less and leveled off at a maximum field of 6.6 T after three to five quenches. Similar results have been obtained in four 1-m models test at LBL. The most recent model at LBL quenched first at 6.4 T and leveled off at 6.6 T. In the next few months, several additional training curves will be obtained from 1-m and 4.5-m models. We expect the recent excellent results to continue, thus allowing the training of the magnets to be conveniently done in long strings after installation in the tunnel if required.

c. Distributed Correction Coil Design. BNL has an active program to develop externally powered distributed correction coils for D. The early 4.5-m models contain coils manufactured at BNL and their performance is being ascertained. Later 4.5-m models and the 16-m models will contain correction coils of the multiwire type, a derivative of printed circuit technology that promises to be particularly cost effective in production. Samples of such coils 4.5-m long are already in hand and meet the required specifications for accuracy and include the necessary bonding agents and electrical performance characteristics when installed on the magnet bore tube. At FNAL (Ref. 17) and LBL (Ref. 21), programs are underway to develop passive distributed correction coils and have given promising results, but further engineering development will be required to integrate these concepts into SSC models.

BNL has extensive experience in the problems of distributed trim coils by virtue of having fully developed and tested externally-powered distributed correction coils for the CBA magnets, of more complicated design (3 multipoles) than needed for SSC. It is anticipated that fully developed coils will be included in at least some of the 16 m magnets scheduled for next year. Should the development of small filament superconductor negate the need for distributed trim coils, their further development and the associated costs would be curtailed.

V.B.2 Continuing Engineering R&D Studies for Design D. Continuing R&D issues to be resolved for magnet Design D (plus A and B) is summarized in Table V.1.

Table V.1 R&D Status (Response by BNL, FNAL and LBL).

Item[a]	Status For Design D	Expected Completion Date For Design D
1) a) Collar stress analysis	R&D work nearly completed; 8T at 2K operation demonstrates adequate safety margin	Last Quarter FY85
b) Other stress analysis	Underway; will be vertified in test of first 16.5 m magnet	Mid FY86 for analysis; verification in late FY86 on PST[b]
2) Electrical system performance analysis and test	Analysis underway	Experimental verification in late FY86 on PST
3) Vacuum system performance analysis and test	Analysis underway	Experimental verification in late FY86 on PST
4) Cryogenic system performance analysis and test	Design and Calc. near completion	Performance verification in full length unit early FY86. System performance from PST in late FY86.
6) Bore tube coating	R&D for plating	1st samples late FY85 full length samples FY86
7) Interconnections		Design nearing completion verification in PST.
8d) Random errors	FY85 effort will provide additional input for errors used in aperture studies	Will continue through production
8f) Alignment and Suspension	Prototype studies completed in FY85 as part of the cryostat development.	Verification first long models by mid FY86
15) Quadrupole development	Preliminary design complete, engineering design could begin immediately	Schedule to be determined by optimum resource allocation

[a] The numbers in the first column refer to the numbers in the list of R&D items given in Section V.A.

[b] FNAL preliminary string test

3. Additional R&D Needed for Reference Design A. Assymmetric iron ires additional calculations using existing codes and subsequent rimental verification particularly with the use of collars and with model ets of the required aperture. The 3.2 cm 2-in-1 magnet test data (4 each m 2-in-1 models), however, does establish an excellent data base to build f a Type A magnet is chosen. In other respects, the R&D requirements identical for those of Design D.

4. Additional R&D Requirements for Reference Design B. There is no tional R&D, beyond that discussed for Design D, required for Design B.

V.B.5 Response to R&D Questionnaire Discussion of Remaining R&D For SSC Reference Design D - Engineering Development

Report to Magnet Technical Review Panel

July 11, 1985

1a) **Basic clamping or collar stress analysis.** Extensive calculations have been performed at BNL (using the finite element program ANSYS), FNAL, and at LBL. The results of these calculations closely predict the final measured deflections of the collar at room temperature while under load at the required prestress. Measurements at LBL using strain gauge instrumentation have confirmed the expected changes in shape upon cool down and due to Lorentz forces when the magnet is powered. Still to be done are calculations on the dynamic behavior of the collar-press system during the actual collaring operation. This would aid in refining the press contact points on the collar so as to better control the deflections during collaring, thereby perhaps permitting the possibility of increased prestress on the coil upon completion of collaring.

1b) Other stress analysis, including shields. With collars containing the Lorentz forces, the remaining forces acting in the magnet are small. The stainless-steel skin forming the helium containment around the outside of the iron yoke is stressed upon completion of the welding operation and further stressed upon cool down due to differential contraction of the stainless steel relative to the iron. These welds have been designed to withstand the required relatively small forces that act to keep the iron yoke firmly closed at the midplane. The large section of the final weldment gives the structure sufficient rigidity to counteract the anticipated bending and torsional forces provided the structure is assembled straight in the first place, as planned.

Engineering analyses of these possible deflections exist and no problem has been found which could lead to later trouble. The remaining development in this category is to measure final deflections when a 16 m cold mass is built. For the cryostat assembly and shield system, FNAL (Ref. 16) has performed extensive calculations and has made measurements on full-length engineering models to verify the correctness of the calculations. From this work, the forces and deflections are well understood, and even the availability of the first full-length magnet will not impact significantly the advanced state of development here.

2) Electrical system performance analysis and test. The electrical system performance analysis for the proposed D magnet system is straightforward owing to the very great electrical similarity of the proposed magnets to the Tevatron and CBA systems. The single approximately 6000 A current leads to an uncomplicated design. The inductance of the 16 m magnets is similar to that of the CBA 5-m magnets, which were extensively tested in an exhaustive string test in the tunnel. Nevertheless, development can only be said to be complete when performance of final magnets is studied in the proposed string tests. The diode protection system needs 7000 A diodes versus the 5000 A diodes exhaustively tested for CBA. These are similar and available, and a test program is underway to confirm their suitability.

3) Vacuum system performance analysis and test. Final engineering development must await the results of the synchrotron radiation experiments currently being conducted at the NSLS. It may be necessary to incorporate a liner in the bore tube to guard against vacuum degradation from the impact of synchrotron radiation at 20 TeV. Other vacuum aspects of the proposed magnet system, such as the pump-down speed following magnet replacement, all meet acceptable parameters of performance.

4) Cryogenic system performance analysis and test. Testing at FNAL (Ref. 16) during the past year has confirmed that the low heat leaks specified in the Reference Designs Study are possible. Whether the anticipated low heat leaks for a complete system of magnets is possible must await the results of the long string test, where end effects will not mask the measured performance. The tests will begin on the preliminary string test at FNAL when two or more magnets are available for interconnection, but the sensitivity of the PST may not be sufficient to finally resolve all the questions.

5) Quench behavior analysis. Good progress has been made in the past year in our ability to predict the temperature upon quench in a cos Θ magnet. The predictions invariably give too high a temperature, probably because it is not possible to construct an analytic model of the effect of the helium cooling. The effective quench velocities are believed to be higher than thus far measured. By normalizing to direct temperature measurements (Ref. 14a) during controlled quenches on CBA models and on SSC 3.2-cm models, the calculations indicate the Design D is safe for passive diode protection. Measurements on 4.5-m D models will soon be made and will provide another normalizing point for the calculations, but the final answer can only come from measurements on the early 16-m models. If passive quench protection is acceptable for this design, a whole host of questions concerning the reliability, complexity, and expense of an active system immediately disappears, and the active heaters now incorporated and being tested in the D magnets can be removed from the design and from future magnets.

6) Bore tube plating feasibility. BNL currently has two R&D contracts with two experienced firms to develop an acceptable copper plating technique. Short samples are already on hand and longer samples are expected later in the year. The two proposed techniques differ from one another (one uses deposition

from a solution containing copper and the other depends on deposition via chemical transport from a copper electrode) and the resulting plated tubes will have a different set of surface characteristics. If successful, these techniques will avoid a welded bore tube which has been shown to always have some (variable) magnetic characteristics. When longer plated bore tubes arrive at BNL, they will be tested for the desired characteristics and if possible, tested in the experiment at the NSLS. Some thought is being given to rf impedance measurements but it may not be possible (or necessary) to measure the precise value of the (expected) very low rf impedance without developing new instrumentation and techniques; guidance and support from the CDG are needed here.

7a) Interconnections design - mechanical. The detailed design of the interconnection region between magnets is proceeding, including layouts, sizing and availability of bellows expansion joints, support structures, etc. Much of this detail will be included and will be proven in the construction of the PST at FNAL, where extensive experience with the Tevatron exists.

7b) Interconnections design - electrical. The electrical system is in detailed design and interconnection layouts are being prepared. Conservative criteria are being used to size the copper interconnection bus work. The current requirements are somewhat higher than for the Tevatron and CBA and similar to those of HERA, where an experienced electrical engineering firm (BBC) is helping to define the design. BNL is watching this evolving design closely. The bus expansion joints are modifications of the exhaustively tested joints developed for CBA. The engineering development will be complete only when a "final" system is assembled and tested in the PST at FNAL and later more thoroughly in the long string test. The detailed work that has been done indicates a non-trivial amount of hardware and a substantial cost impact for a fully-detailed and acceptable system -- an aspect not completely appreciated until detailed design was undertaken.

8a) Model Tests - training. Two D models have been tested at BNL and have reached 6 T with one quench or less and leveled off at the maximum current after five quenches or less. Similar results have been obtained in five 1-m models tested at LBL. This is considered acceptable performance for the specifications of the magnet. Additional models soon to be tested at BNL will give further information on the stability of the result. The coil prestress will be varied in some future models to study the effect of this parameter on quench behavior.

8d) Model tests - random errors. Extensive random error calculations at the three laboratories collaborating in this design (Refs. 22, 10c, 10d) agree closely with one another and with the performance of the CBA and Tevatron magnets. It is felt that the calculations are conservative and that the measured random errors may not be as large as the calculations indicate. There is some evidence that this will be the case from the results of the first BNL model, where every unallowed multipole was substantially less than the rms value predicted. In this design, the random errors are dominated by coil construction errors. Utilizing previous experience, BNL has designed and constructed a new curing press of great strength and exact dimension. The press is constructed of laminated form blocks which are more precise than the former single-piece machined form blocks. It is anticipated that coils molded in this device will be close duplicates of one another as already indicated by the small random error content in the first 4.5-m magnet, which is constructed of four individual coils fabricated with this new press. Measurements of the upcoming models will give a clearer picture of the random errors that can be expected.

Also expected to help this problem are the new precision cabling techniques being developed at LBL and the work to measure and perhaps control cable dimensions being conducted at FNAL.

8e) Quench heating. The technique for direct temperature measurement via Cu resistivity at various points in the coil for a variety of temperature and energy deposition conditions has been by now well developed at BNL. It remains to make these measurements in a future D 4.5-m magnet and a confirmation measurement in a future 16 m magnet. The 4.5 m measurement should be available late in the summer and has not yet been done because of the higher priority accorded the tests for quench behavior and magnetic field quality.

8f) Alignment design. The D design has included special consideration of the necessity for precision from the start. Thus, a careful review of the design features of the D cross section will reveal that the coil is keyed to the collars, the collars to the iron yoke, and the iron yoke via special fiducial apertures in the lamination stamping, to the cold mass support system. An error budget of maximum possible error at each of these interfaces reveals a system well within the required alignment precision. The stiff cold mass assembly, unburdened with unsymmetrical and unbalanced forces, gives confidence that the required alignment precision will be retained in service. Verification of dipole field angle alignment should be possible with the initiation of horizontal testing at FNAL next year, using the "mole" under development at BNL.

9) Production engineering design, manufacturing plan, and testing plan. The extensive production facilities and expertise at FNAL, BNL and continuing discussions with industrial firms have made it possible to make extensive progress in this area. FNAL has extensive experience in this regard, having assembled all the Tevatron and antiproton source magnets in-house from

industrially produced sub assemblies. The Laboratories have engineering talent in-house with extensive industrial manufacturing experience and, utilizing this talent, has developed complete manufacturing plans for CBA and SSC reference design. Engineers from GD, Westinghouse, and BBC have visited BNL and FNAL. General Dynamics completed a contract to develop an example manufacturing plan. The SSC reference design manufacturing plan was reviewed by GD and BBC under contract and found to be reasonable. BNL has purchased industrially manufactured magnets for RHIC and has worked with BBC and DESY on the manufacturability of the HERA magnet.

With the difficult R&D for Design D taking place at three laboratories, a fully developed set of blueprints will be available for a magnet to be manufactured by industry with a minimal need for changes in the design. Experience shows that change orders, no matter how trivial, can be expensive.

A further consideration in this category is the modularity of the basic magnet design. Such modularity is extremely desirable from a manufacturing perspective, for it allows greater automation and minimizes the need for synchronization of component fabrication. Molded coils can be built with tooling designed specifically for this one function and need not interact with yoke assembly, for instance. The collar assembly, yoke stacking, and helium containment operations likewise can all be accomplished on automated machinery dedicated to these functions. The manufacturability of the design has always been a prime consideration in the evolution of the D magnet and has been greatly aided by the knowledgeable engineers who participated in its design. The "expensive tooling" necessary to build early R&D models will translate into less expensive production magnets, and the pay-off promises to be large indeed. These considerations are not so obvious to R&D physicists accustomed to thinking in terms of one-of-a-kind detectors but thanks to the experienced engineers at BNL, FNAL and LBL, are included in the current D magnet.

11a) Lumped correction coils. As part of the Tevatron, a system of five hundred lumped superconducting correction coils was built and has operated in a very reliable way at FNAL. There has been little recent effort in this area, because the requirements for lumped correctors will depend on a forthcoming detailed lattice design. For the Reference Designs Study, a conceptual drawing of a possible corrector design was prepared, using the best information available at the time. It did not then appear that there were any particularly difficult problems in this area.

11b) Distributed correction coil design. BNL has an active program to develop externally powered distributed correction coils for D. The early 4.5-m models contain coils manufactured at BNL and their performance is being ascertained. Later 4.5-m models and the 16-m models will contain correction coils of the MULTIWIRE type, a derivative of printed circuit technology that promises to be particularly cost effective in production. Samples of such coils 4.5 m long are already in hand and meet the required specifications for accuracy and include the necessary bonding agents and electrical performance characteristics when installed on the magnet bore tube. At FNAL (Ref. 17) and LBL (Ref. 21), programs are underway to develop passive distributed correction coils and have given promising results, but further engineering development will be required to integrate these concepts into SSC models.

BNL has extensive experience in the problems of distributed trim coils by virture of having fully developed and tested externally-powered distributed correction coils for the CBA magnets, of more complicated design (3 multipoles) than needed for SSC. It is anticipated that fully developed coils will be included in at least some of the 16 m magnets scheduled for next year. Should the development of small filament superconductor negate the need for distributed trim coils, their further development and the associated costs would be curtailed.

13) Status of production testing instrumentation. Production testing instrumentation can only realistically be undertaken when the magnet design is ready for industrial production. The items which fall into this category, e.g. gauges, calipers, micrometers, sizing and alignment jigs, CODEX machines, etc., are all standard industrial items. A rigorous quality control program will be essential, and will be possible because of the extensive design effort, testing, and intimate knowledge of detail presently being accumulated in the three laboratories involved in the D collaboration.

15) Quadrupole design. A design has been developed and engineering drawings are currently being prepared for an acceptable quadrupole for the lattice. This problem appears susceptible to straightforward development work and no serious problems are anticipated. Given the required characteristics, R&D models could be designed and built in approximately one year. The experience at FNAL in building high gradient quadrupole magnets for SLAC will prove useful.

V.C. Superferric Style Magnet R&D Program (TAC Response)

The Texas Accelerator Center has been working with General Dynamics on a design that was fixed February 15, 1985. We believe this design is mechanically, electrically, and magnetically sound. The design permits very easy assembly with simple tooling. Industry is already assembling the magnet. By the end of CY85 ten channels of 1-m magnets, two channels of 7-m magnets, and 6 channels of 28-m magnets will have been constructed and tested. The funding for this program (except for the testing) has already been committed from FY85 resources. This will provide a sufficient data base to construct 24 35-m magnets in industry during CY86. This could be accomplished with the same level of resources allocated to the FY85 total magnet program.

This program of solid accomplishment coupled with the long experience with iron magnet accelerators and colliders will provide a magnet design ready for SSC production in industry by 1987.

The attached schedule shown in Fig. V.2 for superferric magnet production, indicates that the SSC preproduction dipole magnets could be completed by the end of CY 1986. This assumes participation by all laboratories, for example, TAC overseeing magnet production in industry, lab 1 measuring magnets, lab 2 responsible for spool piece production, and lab 3 helping on smaller items (position monitors, etc.)

V.C.1. Significant Engineering R&D questions to be Resolved for Design C

a. Field calculations. The programs used by the TAC for magnetic field calculations are POISSON and MAGNUS (Ref. 12). POISSON is the standard 2-dimensional program and predicts Design C multipoles to about 5/n units (parts in 10^4). We plan improvements in this program in two areas, first the permability and its derivatives are

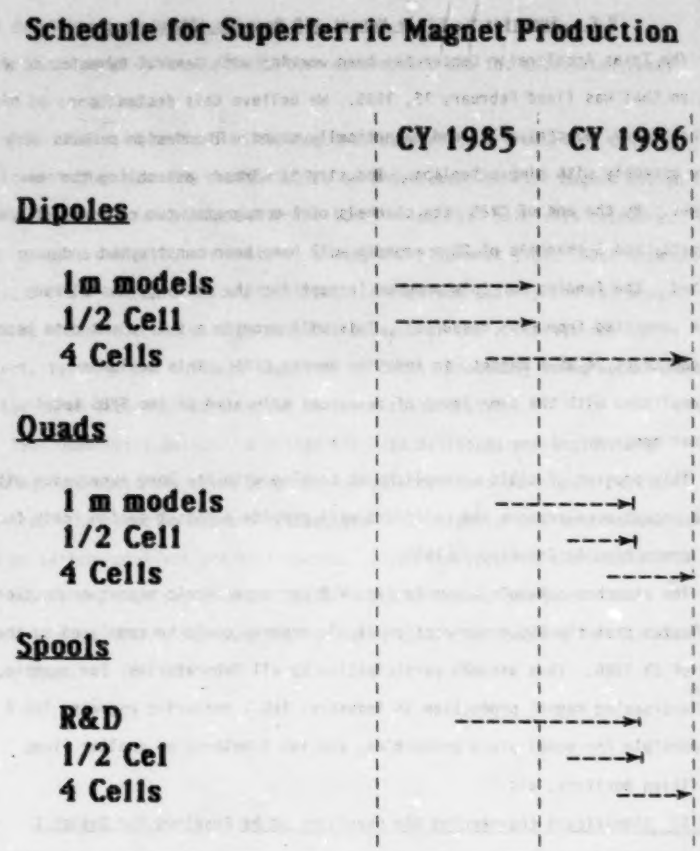

Fig. V.2 FY 1986 schedule for Design C.

not always treated properly and, second, the meshes used in the program could be improved. MAGNUS is a 3-dimensional program which is being used at TAC for the superferric magnet design. Some auxiliary subroutines are needed for interpretation of the solutions. Necessary modifications to these programs will be completed before the end of this year.

b. Control and measurement of permeability. TAC has a program outlined to measure the permeability of the iron used in the magnets. Samples of individual magnet laminations as well as each 6 in. pack of iron laminations will have the permeability measured at 2 points (mid and high field) and the remanent field for injection. Shuffling of the 6 in. packs such that the equivalent permeability averages to the same value within a few parts of 10^3 over each 10 meters length will permit control of multipoles (the effect due to permeability) to a few parts in 10^5. This technique will be verified in the next 12 magnet channels that will be assembled in this manner.

c. Continued testing of models. The final design of the superferric magnet has been fixed since February 15, 1985. Four each 1-in-1 one meter models have been constructed and tested. By the end of CY85 an additional 4 each 2-in-1 one meter, at least 1 each 2-in-1 seven meter, and 3 each 2-in-1 twenty-eight meter magnets will be constructed and tested. The three long magnets will be assembled at General Dynamics and tested at TAC. Measurements of multipoles, quenching characteristics, cryogenics and alignment will be done.

V.C.2 Continuing Engineering R&D Studies for Design C. Table V.2 is similar to Table V.1 in showing the areas of continuing R&D program as forseen at TAC. The detailed response is given in the following section.

Table V.2 R&D Status (Response by TAC).

	Item[a]	Status for Design C	Expected Completion Date For Design C
1.	Collar stress analysis	G.D. Contract Being Negotiated	6 Months After Start
2.	Electrical system performance analysis and test	Under Analysis	Half Cell Test (begins 1-86)
3.	Vacuum system performance analysis and test	Analysis Underway	Experimental Verification in Late 86 (half cell test)
4.	Cryogenic system performance analysis and test	Design and Analysis	Experimental Verification Half Cell Test
5.	Quench behavior	Analysis Nearly Done	Experimental Verification in Half Cell Test
6.	Bore tube coating	Samples Being Made	First Samples in Late FY85; Full Length Samples FY86.
7.	Interconnections	Design Underway	Mechanical Mock-up 1st Quarter FY86; Prototype Interconnection Tests Included in Half Cell
8d.	Random errors	Model Tests	Continue Through Production
8f.	Alignment and suspension	7-m model	Continuous
15.	Quad development	Design	1 Meter Model By 1st Quarter FY86

[a] The numbers in the first column refer to the numbers in the list of R&D items given in Section V.A.

V.C.3 Response to R&D Questionnaire by TAC Discussion of Remaining R&D For SSC Reference Design C

Report to Magnet Technical Review Panel
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1. Stress analysis.

A contract with General Dynamics-Convair for complete stress analysis of the superferric magnet is being negotiated now. Once started, it will be complete in six months.

2. Electrical system performance analysis test.

The 3 T superferric magnet system has four independent currents, two 12,000 A loops and two 3,000 A loops. These permit independent control of the dipole, quadrupole, sextupole, and decapole magnetic multipoles. Test of these systems will be done when the half-cell tests begin in January, 1986.

3. Vacuum system performance analysis and test.

Final engineering development must await the results of the synchrotron radiation experiments currently being done at the NSLS. Experimental verification in late CY86 on half-cell test.

4. Cryogenic system performance analysis and tests.

The vast experience of CCI, the superferric cryogenic designers, on helium service and, in particular, the FNAL Energy Doubler, gives confidence that the cryogenic system will perform as calculated. Only operation of the magnet string will confirm this. Experimental verification in late CY86 on half-cell test.

5. Quench behavior.

Two independent computer programs have been used to predict quench behavior. These are required to verify the temperature in the cable. Experimental verification in late CY86 on half-cell test (Ref. 8).

6. Bore tube coating.

University of Wisconsin with industry is developing a method of rolling copper onto stainless steel and then forming a tube. Short samples have been done. Actual bore tubes will be done next, in FY86.

7. Interconnections design.

The 105 m superferric magnet contracts 33 centimeters during cool down. Mechanical mock-up of conductor coils and bellows containing cryogens will be tested by the end of the year. Prototype will be tested during FY86 on the half cell test.

8d. Model tests - Random errors.

Twelve of the final design magnet channels will be measured over the next six months. This program will continue throughout the entire production (Ref. 12).

8f. Model tests - Alignment.

During the next six months one 7-m magnet and three 28-m magnets will be tested and studied.

11. Spool pieces - Correction elements, etc.

Conceptual design has been done. Detailed design needs to be done.

13. Production testing instrumentation.

The superferric magnets would be tested cold, since there are only 1330 units that go in the tunnel. Full testing (needs studying) would be done.

15. Quadrupole design.

Computer designs are being generated now. The first 1-meter quad should be complete by the end of this year. Full length quadrupoles by mid FY86.

APPENDIX A

CHARGE TO THE TECHNICAL MAGNET REVIEW PANEL
October 19, 1984

Members

Alvin Tollestrup, Chairman

Dr. T. Elioff, LBL

Prof. F.R. Huson, TAC

Dr. P. Limon, CDG

Dr. R. Lundy, FNAL

Dr. R. Neal, SLAC

Dr. P.J. Reardon, BNL

Dr. C. Taylor, LBL

Dr. R. Watt, SLAC

Mr. R. Yourd, CDG

1. Delineate for each design type that minimal set of technical data which is needed for the design type selection process and which can only be obtained from models and prototypes.
2. Review critically the report progress, from October, 1984, to date, of each of the three major design types.
3. Review critically plans for FY85 in light of (1) and, as appropriate, suggest changes which may enhance their effectiveness.
4. Write a report setting forth the results of (1), (2), (3), in a systematic fashion.

APPENDIX B

CHARGE TO THE TECHNICAL MAGNET REVIEW PANEL
April 23, 1985

Members

Alvin Tollestrup, Chairman

Prof. H. Hirabayashi, KEK	Dr. C. Taylor, LBL
Prof. F.R. Huson, TAC	Dr. R. Watt, SLAC
Dr. R. Lundy, FNAL	Mr. R. Yourd, LBL
Dr. P.J. Reardon, BNL	

1. Review magnet and cable development programs at BNL, FNAL, LBL, and TAC.
2. Write a report evaluating the technical status of dipole and quadrupole magnet design and development work for the 1-in-1 and 2-in-1 low- and high-field magnet styles. For each style enumerate the R&D remaining before each style can prudently be carried to the full-scale prototype stage. This enumeration should include an estimate of the time and manpower effort needed to complete the pre-prototype R&D. The report should include a detailed account of model tests for the various designs.
3. Evaluate and report on the status of superconducting cable development and enumerate further development objectives which could reasonably be expected to be complete in time to have a beneficial impact on SSC magnet cost, reliability, and ease of operation. The report should be complete by July 25, 1985.

APPENDIX C. TEST DATA

This appendix contains the results of model magnet measurements as of the end of July, 1985. An updated set of data will be available before the end of August for use by the Basic Magnet Type Selection Panel. The data collected here have not been digested and are only provided as illustrations of the type of data being obtained by the various centers. The data for type D from BNL show the training curves and harmonics as a function of current for the first two 4.5-meter models.

The data from LBL are for two 1-meter models using the D-type collars.

The data from FNAL are room temperature measurements made on four 1-meter models with a 5 cm bore using the "dry winding" technique. The shims were not correct and, hence, the large value of b_2. The tables are interesting in that they show the quality of coil achieved by the dry winding technique. A good measure of the random errors are given by the a_n and the odd b_n. In addition these data illustrate the quality of measurements that can be achieved at room temperature with a rather simple test setup. The monitoring of magnet production at room temperature provides one of the most effective means for component and construction quality control.

Data from TAC are for the first two 1-meter models and were obtained early in the program. The tables show three successive runs and these numbers can be compared for reproducibility of the data. Later the magnet design was modified from two windings to three independent coils. Data from this style magnet near 3 T with currents adjusted so that b_2 and b_4 are nearly cancelled are given in the table. Extrapolation of these data by means of a least squares linear fit yields a value for the current where $b_2 = 0$ of 11,202 A and for where $b_4 = 0$ of 11,180 A. The predicted value from the computer is 11,260 A. The data are from GD1.

4.5 m DIPOLES FOR BNL REFERENCE DESIGN D: PERFORMANCE UPDATE

Tests on the second 4.5 m long model dipole for Reference Design D (1-in-1, collared coils, 4.0 cm aperture) started on July 15, with a first quench at 6.03 T (5894A) and a quench plateau (at 4.5 K) of about 6.60 T (6520A) reached with negligible training. This plateau is virtually identical to that observed with the first dipole at this temperature, as in evident from the two enclosed graphs showing field vs. quench number for the two magnets. It is also in reasonably good agreement with the "short sample" prediction at 4.5 K--i.e., the quench field expected from laboratory measurements on short samples of the conductor utilized in the magnets. At the time of writing, the second magnet had not yet attained a clear-cut quench plateau in sub-cooled (2.5K) helium (dipole #1 reached a maximum field of 8.05 T at this temperature).

Similarly, field quality results reported here are also somewhat preliminary. Table I summarizes the allowed (two-dimensional, not integrated) harmonics. Here column 2 gives the calculated (design) values at 1 cm radius (a "unit" is the multipole field at 1 cm radius, normalized to 10^{-4} of the dipole field), obtained with a finite element, variable-μ program with a current of 2 kA (or B_0 2T). Columns 3 and 4 list the measured values, and column 5 the corresponding r.m.s. random multipole errors calculated by Herrera et al. for assumed 0.05 mm (0.002 in.) radial and azimuthal conductor placement errors. Table II summarizes similar data for the skew and normal nonallowed harmonics. As can be seen, the measured harmonics are small, with individual values differing from the design values by no more than an r.m.s. width and showing a magnet-to-magnet variation also well within the r.m.s. band.

BNL DATA

Table I

Allowed Harmonics ($10^{-4}B_0$) at 1 cm)

b_n	Calculated Value	Measured, Dipole No.1	Measured, Dipole N.2	Expected rms Errors
b_2	3.56	1.3	0	2.6
b_4	-0.44	-0.3	-0.6	0.68
b_6	0.17	0	0	0.08
b_8	0.83	0.9	0.8	0.02
b_{10}	-0.02	0	0	0.003
b_{12}	-0.04	0	0	-

Table II

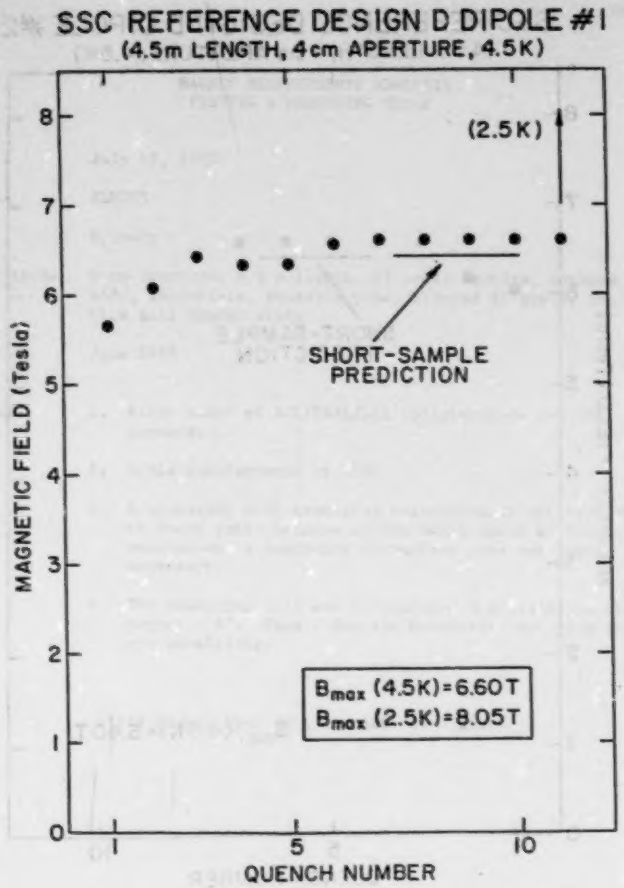
Forbidden Harmonics ($10^{-4}B_0$) at 1 cm

b_n, a_n	Measured, Dipole No.1	Measured, Dipole No.2	Expected rms Errors
b_1	0.1	-0.4	1.8
b_3	-0.1	-0.1	0.57
b_5	0	0	0.06
b_7	0.1	0	0.02
b_9	0	0	0.004
a_1	-1.5	-2.4	3.3
a_2	0.3	0.1	0.65
a_3	-0.4	-0.3	0.73
a_4	0	0.1	0.15
a_5	-0.1	0	0.26
a_6	0	0	0.05
a_7	-0.1	0	0.04
a_8	0.1	0.1	0.008
a_9	0	0	0.009

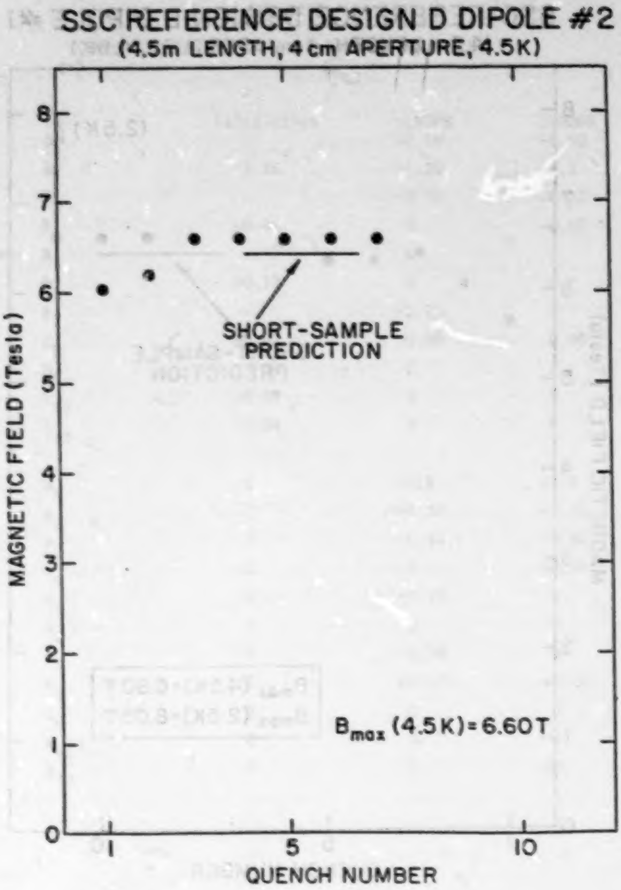
BNL DATA

Comparison of First Two D Dipoles B_0 = 2.07 T

	Calculation	SLM008	SLM009
b_1	-	+0.10	-0.40
b_2	3.56	-1.30	-2.5
b_3	-	-0.10	-0.10
b_4	-0.44	0	-0.20
b_5	-	0	0
b_6	+0.17	0	0.1
b_7	-	+0.10	0
b_8	+0.83	0.90	0.90
b_9	-	0	0
b_{10}	-0.02	0	0
b_{12}	-0.04	0	0
a_1	0	-1.5	-2.4
a_2	0	+0.30	+0.10
a_3	0	-0.40	-0.30
a_4	0	0	+0.10
a_5	0	-0.10	0
a_6	0	0	0
a_7	0	-0.10	0
a_8	0	+0.10	+0.10
a_9	0	0	0
a_{10}	0	0	0
a_{12}	0	0	0



Test Data from first two BNL SSC type D dipoles SLN008 and SLN009.



Test Data from first two BNL SSC type D dipoles SLN008 and SLND09.

MAGNET MEASUREMENTS ANALYSIS
TESTING & MEASURING GROUP

Date: July 18, 1985

Magnet: SLN008

Data: Summary

Description: 4 cm aperture, 4.5 m length, C5 cross section, dogbone ends, SS collars, reusable yoke, clamped SS shell, BNL trim coil heater strip

Tested: June 1985

Comments:

1. First model of BNL/FNAL/LBL collaboration for SSC magnets.
2. Cable manufactured by NEEW
3. A measuring coil centering correction is not applied to these data; because of the small value of the multipoles, a centering correction does not appear necessary.
4. The measuring coil was miscentered vertically in the magnet ~ 4". Thus $\int Bdl$ and harmonics including ends are unreliable.

(This Magnet Test Note consists of 1 sheet)

```
SLH008     CH  07/16/85   22.56.06.   HERRERA/WILLEN ANALYSIS

QUENCHS: N,I(A)=    1  5507    2  5932    3  6317    4  6232    5  6239   28  8186(MAX)  TOTAL= 41
           B(T)=    0.0000     0.0000     0.0000     0.0000     0.0000      0.0000

DC EXC ENDS                      .4764K 07/11/85    MEASURED ON 28-JUN-85  COIL,MAG= 22 4  R2,OM= 0.00   0.0
B' AND A'(E-4) EVALUATED AT X= 1.0 CM
    I      B0    B0/I   ALP'   B1'     B2'     B3'     B4'     B5'     B6'     B7'     B8'     B9'    B10'    B11'    B12'
    A       T     G/A    MR    A1'     A2'     A3'     A4'     A5'     A6'     A7'     A8'     A9'    A10'    A11'    A12'
  100   .1035 10.350    -.1     .7   -11.4      .5     6.6      .1     -.2      .1      .7     -.0     -.2      .0     -.0
                              -2.5     1.7     -.9     1.1     -.3     -.1     -.0      .1     -.0     -.0      .0      .0
  500   .5168 10.337    -.2     .0   -16.0      .0     2.3     -.0      .1      .1     1.2      .0     -.1     -.0     -.0
                              -1.5      .1     -.6      .2     -.2     -.0     -.0      .1     -.0     -.0     -.0     -.0
 1000  1.0350 10.350    -.0    -.1    -5.5     -.0      .6     -.0     -.0      .1     1.0     -.0     -.1     -.0     -.0
                              -1.1      .3     -.4     -.0     -.3      .0     -.0      .1     -.0     -.0     -.0     -.0
 1200  1.2424 10.353    -.2    -.4    -4.1     -.1      .4     -.0      .0      .1     1.0     -.0     -.0     -.0     -.0
                              -1.2      .4     -.4      .0     -.2      .0     -.0      .1     -.0     -.0     -.0     -.0
 2000  2.0711 10.355    -.1     .6    -2.0     -.1      .1     -.0      .0      .1      .0     -.0     -.0     -.0     -.0
                              -1.2      .3     -.4     -.0     -.2      .0     -.0      .1     -.0     -.0     -.0     -.0
 3000  3.1061 10.354    -.3     .1     -.9     -.1     -.0     -.1     -.0      .1      .0      .0     -.0     -.0     -.0
                              -1.3      .4     -.5     -.0     -.2      .0     -.0      .1     -.0     -.0     -.0     -.0
 4000  4.1390 10.347    -.3    -.1      .1     -.2     -.1      .0     -.0      .1      .0     -.0     -.0     -.0     -.0
                              -1.1      .4     -.4     -.1     -.2      .0     -.0      .1     -.0     -.0      .0     -.0
 5000  5.1948 10.310    -.2    -.1     1.1     -.1     -.1      .0     -.0      .1      .0      .0     -.0     -.0     -.0
                              -1.1      .2     -.3     -.0     -.2      .1     -.0      .1      .0     -.0     -.0      .0
 5400  5.5501 10.278     .1     .2     1.4     -.1     -.2     -.0     -.1      .1      .0      .0     -.0      .0     -.0
                              -1.3      .1     -.4     -.1     -.1      .0     -.0      .1      .0     -.0     -.0     -.0
 7401  7.3881  9.983    2.3     .2     1.0     -.1     -.1     -.0     -.1      .1      .0      .0     -.0     -.0     -.0
                              -1.4      .3     -.5     -.1     -.2      .0     -.0      .1     -.0     -.0     -.0     -.0

DC INC ENDS-COIL 4               .2787R 07/02/85    MEASURED ON 28-JUN-85  COIL,MAG= 22 4  R2,OM= 0.00   0.0
B' AND A'(E-4) EVALUATED AT X= 1.0 CM
    I      B0    B0/I   ALP'   B1'     B2'     B3'     B4'     B5'     B6'     B7'     B8'     B9'    B10'    B11'    B12'
    A       T     G/A    MR    A1'     A2'     A3'     A4'     A5'     A6'     A7'     A8'     A9'    A10'    A11'    A12'
  100   .1035 10.354    -.2    -.5     3.4      .4     5.5      .0     -.1      .1      .6     -.0     -.2     -.0     -.0
                              -3.0      .9     -.7      .9     -.2     -.1     -.0      .1      .0     -.0      .0      .0
  500   .5170 10.340    -.2    -.6    -3.0      .1     1.7      .0      .2      .1     1.0     -.0     -.1     -.0     -.0
                              -2.9      .9     -.3      .2     -.2     -.0     -.1      .0      .0     -.0      .0     -.0
 1000  1.0352 10.352    -.1    -.3     6.9      .0      .1      .0      .1      .1      .0     -.0     -.1     -.0     -.0
                              -3.0      .9     -.3     -.0     -.1      .0     -.1      .0     -.0     -.0      .0     -.0
 1200  1.2425 10.354    -.1    -.3     8.1      .0     -.0      .0      .1      .1      .0      .0     -.0     -.0     -.0
                              -3.0     1.0     -.3     -.0     -.1     -.0     -.1      .0     -.0     -.0      .0     -.0
 2000  2.0711 10.355    -.1    -.3    10.3     -.0     -.3      .0      .1      .1      .0     -.0     -.0     -.0     -.0
                              -3.0     1.0     -.3     -.1     -.2      .0     -.1      .0     -.0     -.0      .0     -.0
 3000  3.1048 10.348    -.2    -.3    11.3     -.0     -.5      .0      .1      .1      .0     -.0     -.0     -.0     -.0
                              -3.0      .9     -.3     -.1     -.2     -.0     -.1      .0     -.0      .0      .0     -.0
 4000  4.1341 10.335    -.2    -.1    12.1     -.0     -.5      .0      .1      .1      .0     -.0     -.0     -.0     -.0
                              -3.0      .9     -.3     -.1     -.1     -.0     -.1      .0     -.0      .0      .0     -.0
 5005  5.1430 10.288    -.2    -.2    13.1     -.1     -.5     -.0      .1      .1      .0     -.0     -.0     -.0     -.0
                              -3.2     1.0     -.3     -.1     -.1      .0     -.1      .0     -.0      .0      .0     -.0
 5400  5.5358 10.251     .0    -.3    13.4     -.0     -.6      .0      .1      .1      .0      .0     -.0     -.0     -.0
                              -3.0      .9     -.2     -.1     -.2      .0     -.1      .0     -.0      .0      .0     -.0
 7401  7.3660  9.953    2.3    -.2    13.0     -.1     -.6      .0      .0      .1      .0      .0     -.0     -.0     -.0
                              -3.2      .9     -.3     -.1     -.1      .0     -.1     -.0     -.0      .0      .0     -.0
NOTE: B0 AND B0/I NORMALIZED AT 2000.0 A  FACTOR= 1.1253  EFFECTIVE LENGTH= 0.0000 M

CURRENT(A), INTEGRAL BDL(TM), EFF LEN(M)=  500.0  0.0000 0.0000
CURRENT(A), INTEGRAL BDL(TM), EFF LEN(M)= 2000.0  0.0000 0.0000
CURRENT(A), INTEGRAL BDL(TM), EFF LEN(M)= 5000.0  0.0000 0.0000
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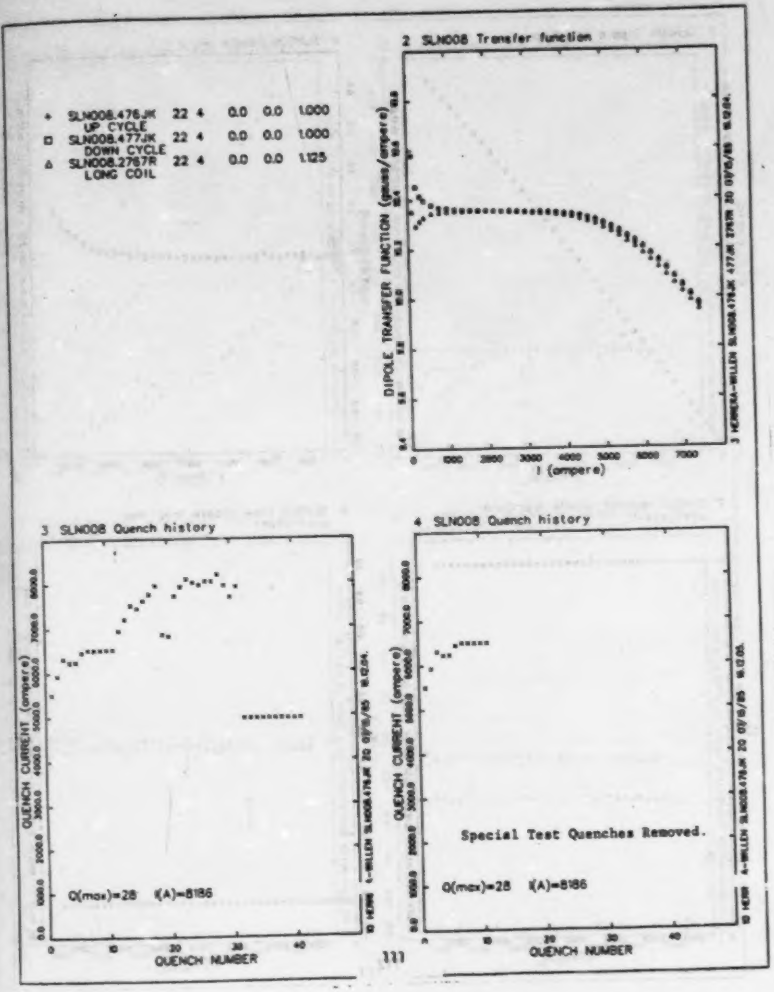
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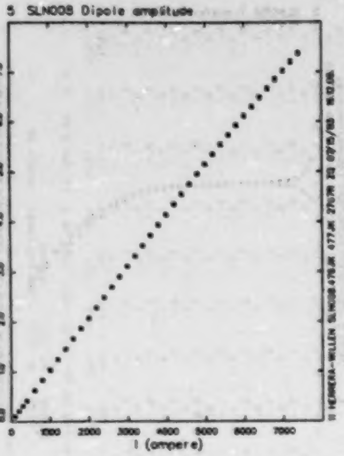
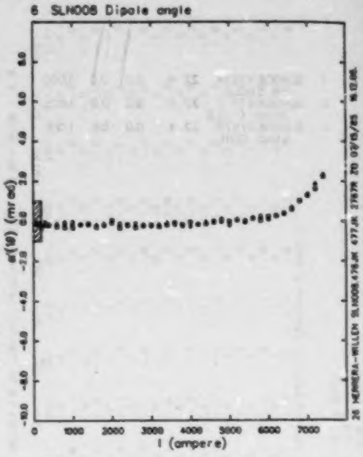
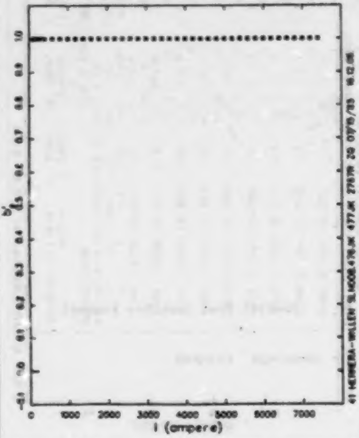
UP CYCLE
□ SLN008.477JK 22 4 0.0 0.0 1.000
DOWN CYCLE
△ SLN008.2767R 22 4 0.0 0.0 1.125
LONG COIL
2 SLN008 Transfer function
DIPOLE TRANSFER FUNCTION (gauss/ampere)
I (ampere)
0
1000
2000
3000
4000
5000
6000
7000
3 HERRERA-WILLEN SLN008.476JK 477JK 2767R 20 07/15/85 15.12.04.
3 SLN008 Quench history
QUENCH CURRENT (ampere)
0.0
1000.0
2000.0
3000.0
4000.0
5000.0
6000.0
7000.0
8000.0
QUENCH NUMBER
0
10
20
30
40
Q(max)=28 I(A)=8186
4 SLN008 Quench history
Special Test Quenches Removed.
Q(max)=28 I(A)=8186
111



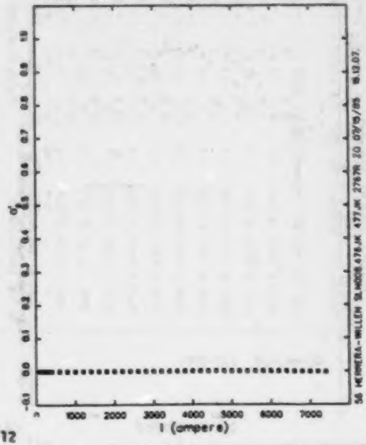
5 SLN008 Dipole amplitude



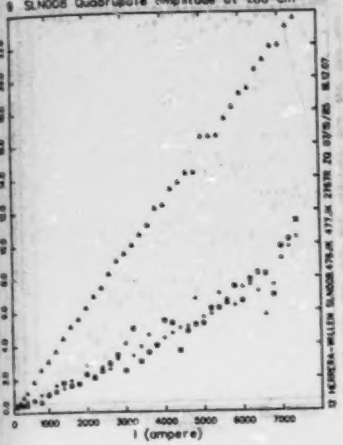
6 SLN008 Dipole angle

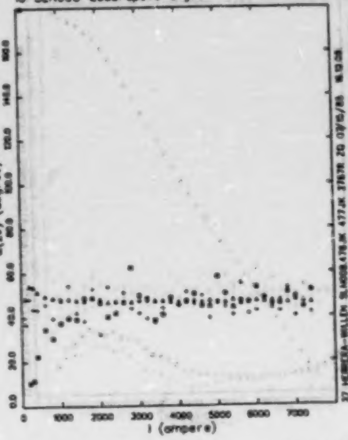


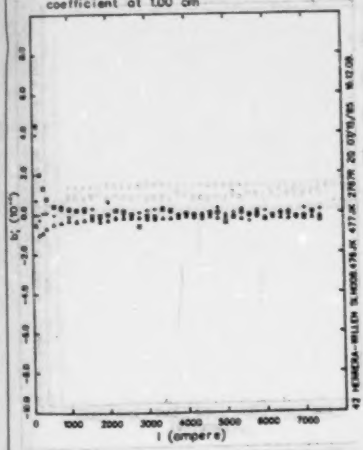
7 SLN008 Normal dipole fractional coefficient

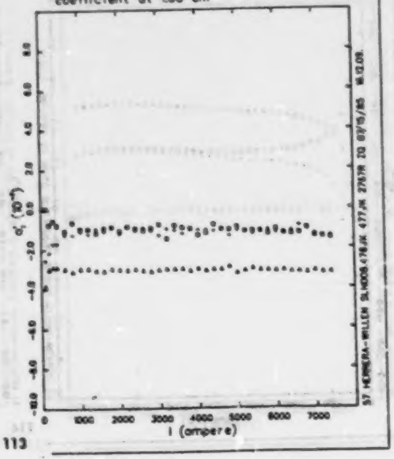


8 SLN008 Skew dipole fractional coefficient

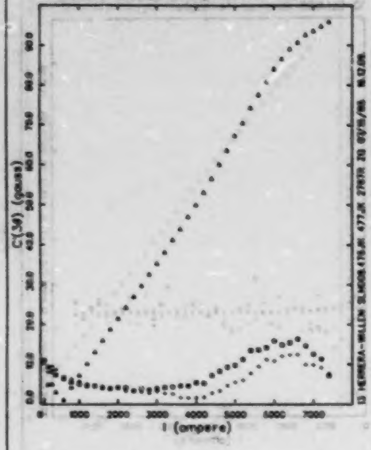

9 SLN008 Quadrupole amplitude at 1.00 cm


10 SLN008 Quadrupole angle

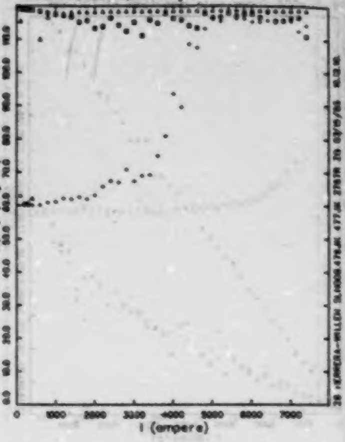

11 SLN008 Normal quadrupole fractional coefficient at 1.00 cm


12 SLN008 Skew quadrupole fractional coefficient at 1.00 cm

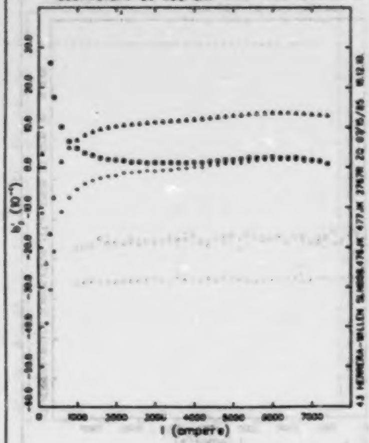
13 SLN008 Sextupole amplitude at 1.00 cm



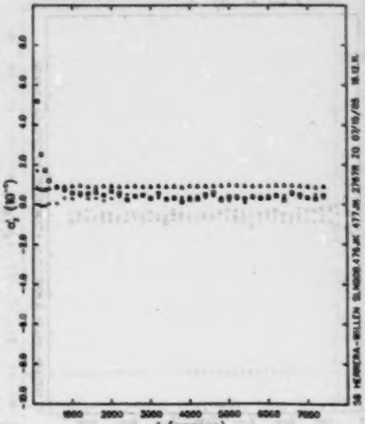
14 SLN008 Sextupole angle



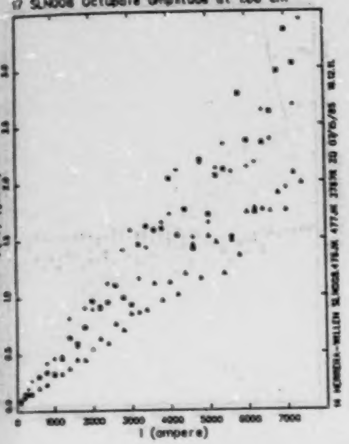
15 SLN008 Normal sextupole fractional coefficient at 1.00 cm



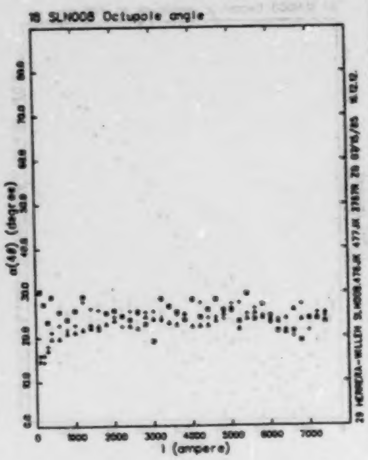
16 SLN008 Skew sextupole fractional coefficient at 1.00 cm



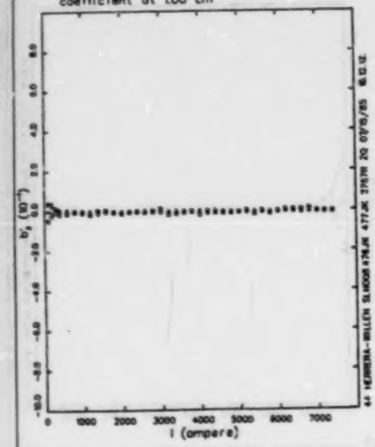
17 SLN008 Octupole amplitude at 1.00 cm



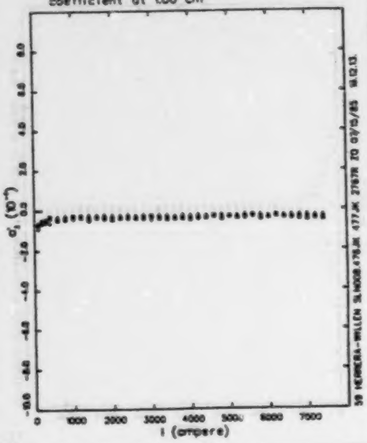
18 SLN008 Octupole angle

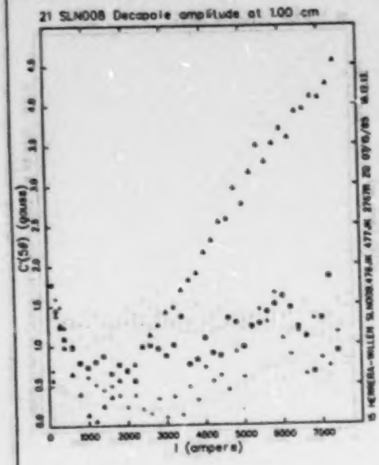


19 SLN008 Normal octupole fractional coefficient at 1.00 cm

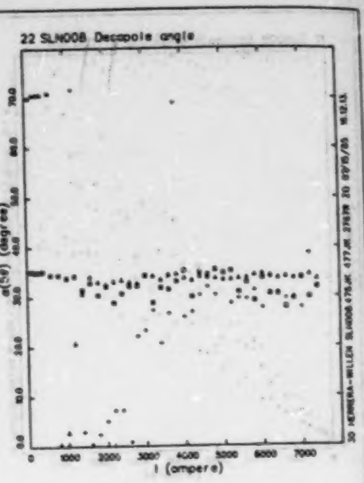


20 SLN008 Skew octupole fractional coefficient at 1.00 cm

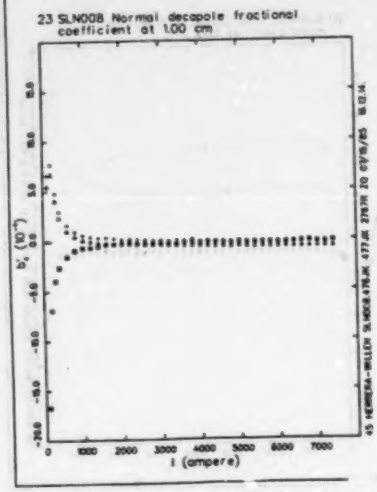




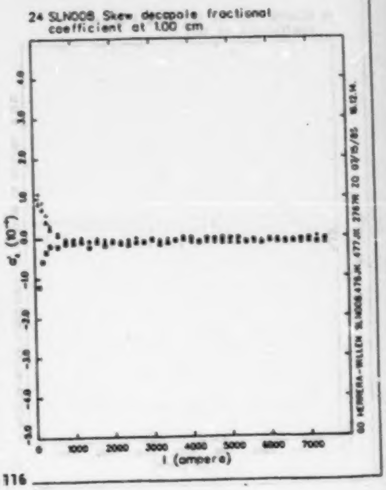
21 SLN008 Decapole amplitude at 1.00 cm



22 SLN008 Decapole angle

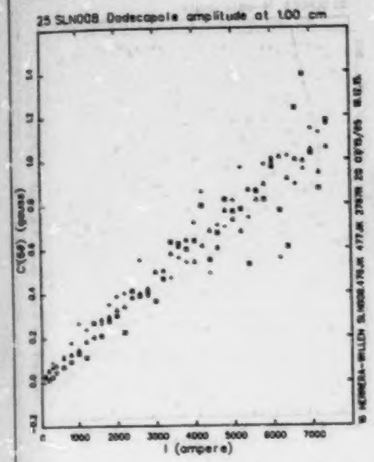


23 SLN008 Normal decapole fractional coefficient at 1.00 cm

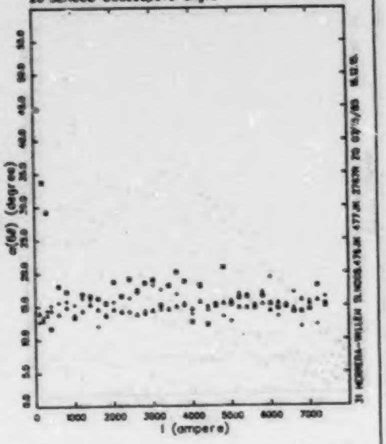


24 SLN008 Skew decapole fractional coefficient at 1.00 cm

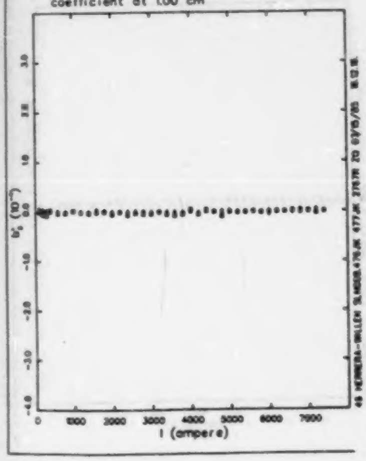
25 SLN008 Dodecapole amplitude at 1.00 cm



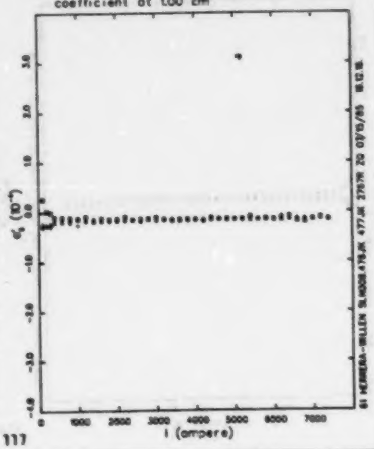
26 SLN008 Dodecapole angle



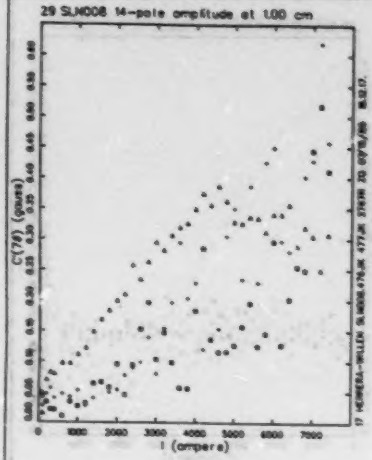
27 SLN008 Normal dodecapole fractional
coefficient at 1.00 cm



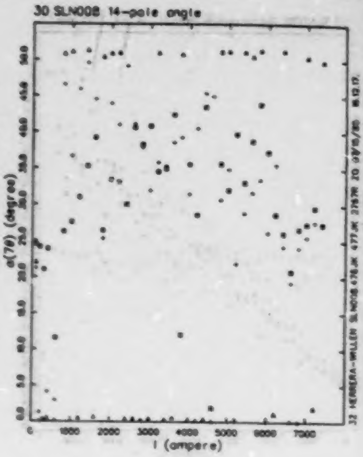
28 SLN008 Skew dodecapole fractional
coefficient at 1.00 cm



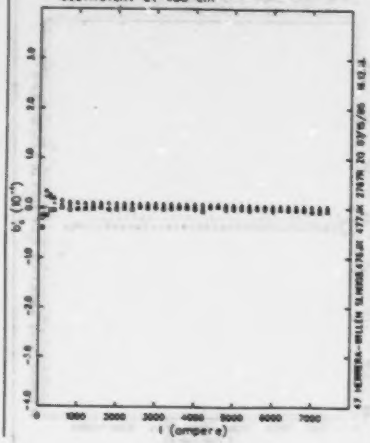
29 SLN008 14-pole amplitude at 1.00 cm



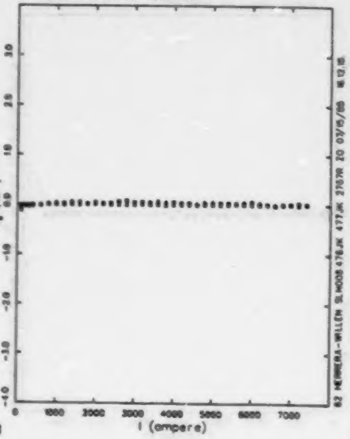
30 SLN008 14-pole angle



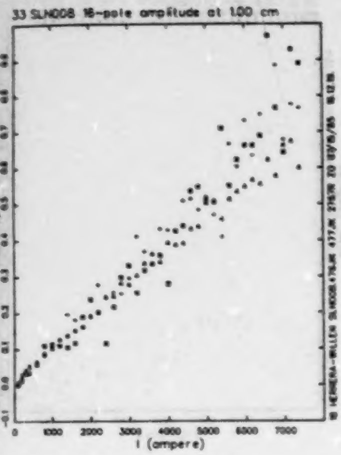
31 SLN008 Normal 14-pole fractional coefficient at 1.00 cm



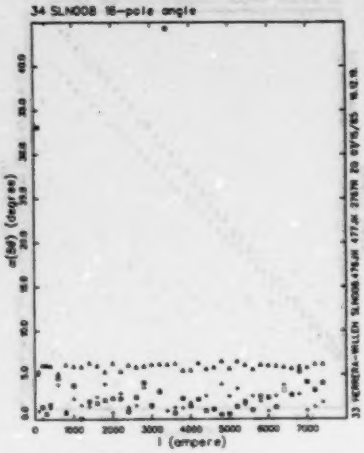
32 SLN008 Skew 14-pole fractional coefficient at 1.00 cm



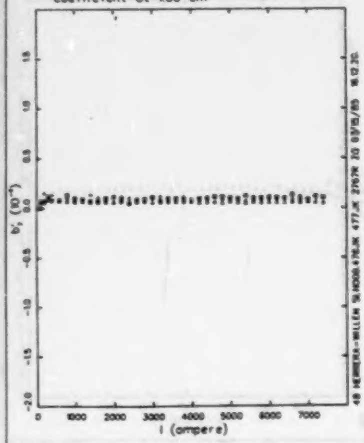
33 SLN008 16-pole amplitude at 1.00 cm



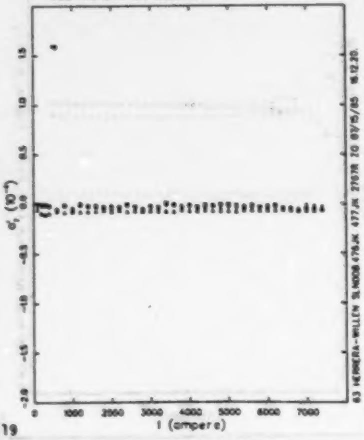
34 SLN008 16-pole angle

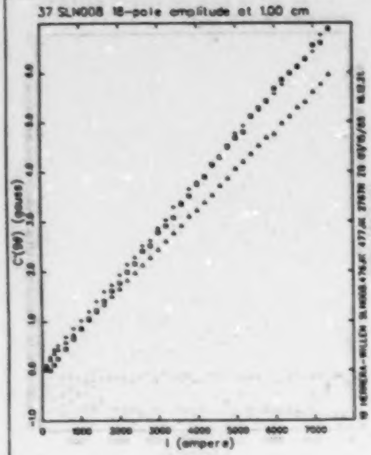


35 SLN008 Normal 16-pole fractional
coefficient at 1.00 cm

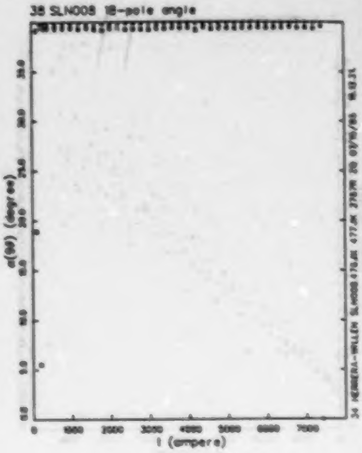


36 SLN008 Skew 16-pole fractional
coefficient at 1.00 cm

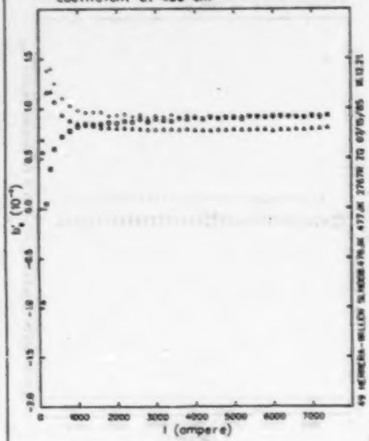




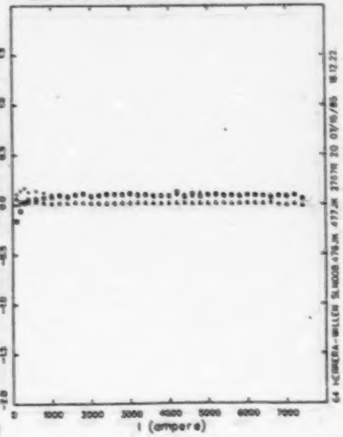
37 SLN008 18-pole amplitude at 1.00 cm



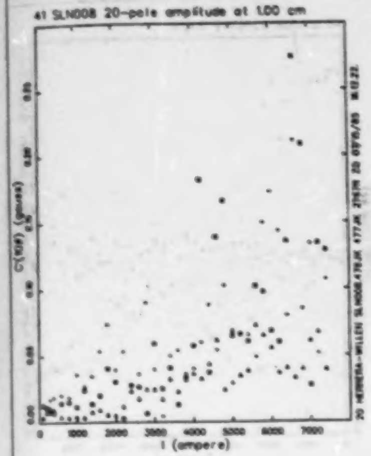
38 SLN008 18-pole angle



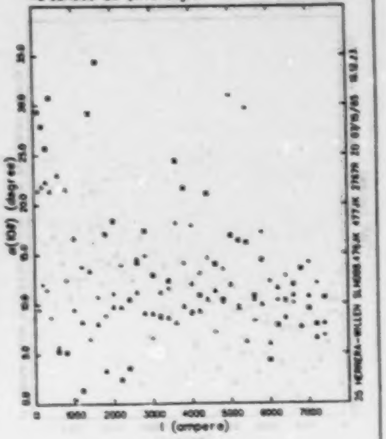
39 SLN008 Normal 18-pole fractional
coefficient at 1.00 cm



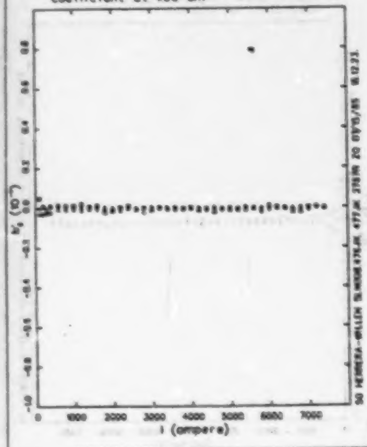
40 SLN008 Skew 18-pole fractional
coefficient at 1.00 cm



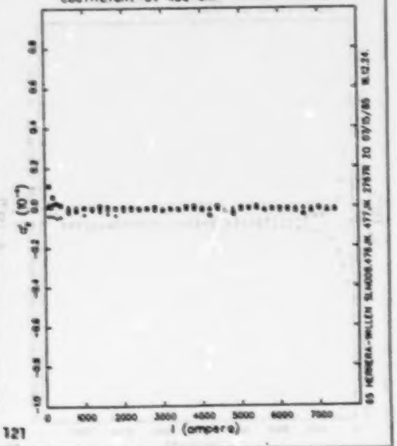
41 SLN008 20-pole amplitude at 1.00 cm



42 SLN008 20-pole angle

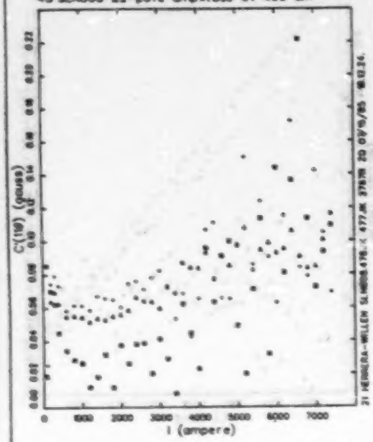


43 SLN008 Normal 20-pole fractional coefficient at 1.00 cm

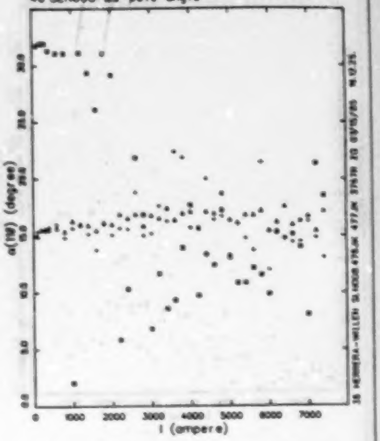


44 SLN008 Skew 20-pole fractional coefficient at 1.00 cm

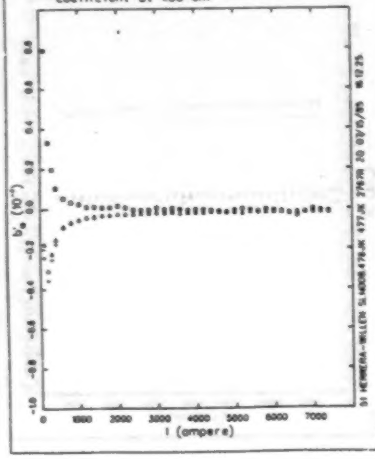
45 SLN008 22-pole amplitude at 1.00 cm



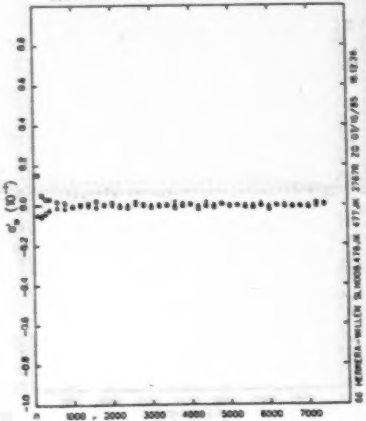
46 SLN008 22-pole angle



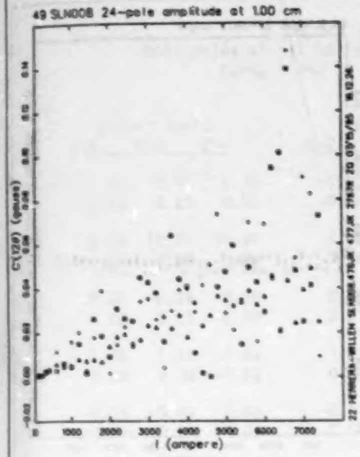
47 SLN008 Normal 22-pole fractional coefficient at 1.00 cm



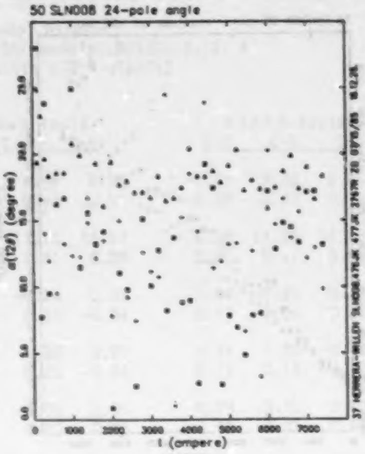
48 SLN008 Skew 22-pole fractional coefficient at 1.00 cm



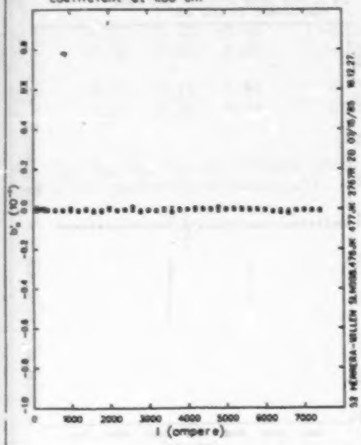
49 SLN008 24-pole amplitude at 1.00 cm



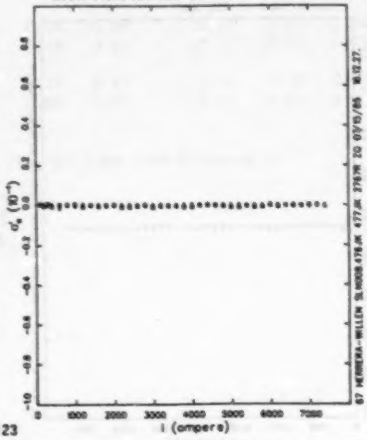
50 SLN008 24-pole angle



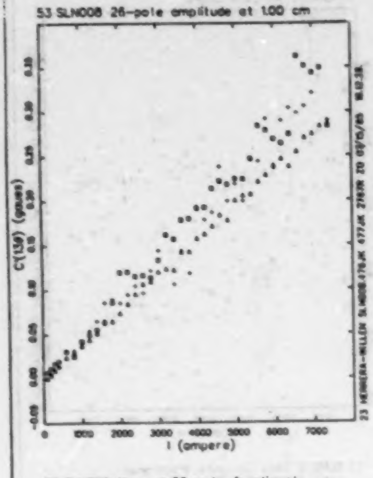
51 SLN008 Normal 24-pole fractional coefficient at 1.00 cm



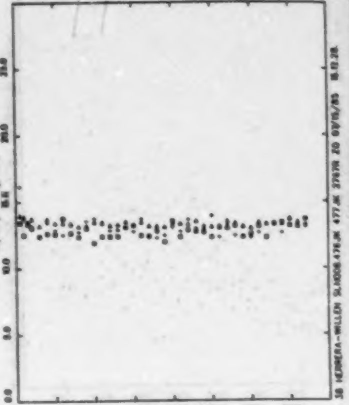
52 SLN008 Skew 24-pole fractional coefficient at 1.00 cm



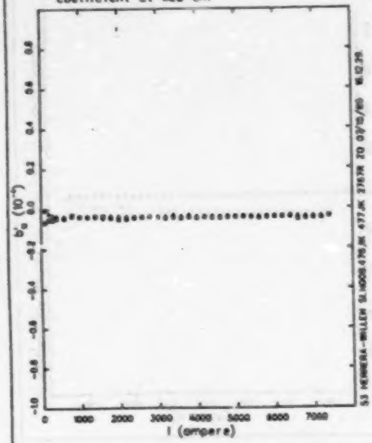
53 SLN008 26-pole amplitude at 1.00 cm



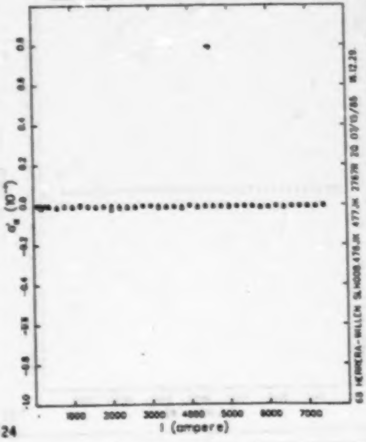
54 SLN008 26-pole angle



55 SLN008 Normal 26-pole fractional coefficient at 1.00 cm



56 SLN008 Skew 26-pole fractional coefficient at 1.00 cm



LBL DATA

LBL SSC Model Dipoles
Multipoles at r=1 cm in SSC models, D-12C- 2, 3, 4
$C_n = b_n + iA_n$ in units (10^{-4} dipole)

	3kA=3 Tesla			2kA=2 Tesla			4 kA=4 Tesla		
	C-2	C-3	C-4	C-2	C-3	C-4	C-2	C-3	C-5
b_1	-1.51	2.96	0.30	-1.52	2.69	0.32	-1.53	3.08	0.27
a_2	-0.55	0.25	0.09	-0.48	0.62	-0.01	-0.59	0.05	0.16
b_2	6.33	12.01	16.54	5.78	11.73	15.87	6.30	11.35	16.68
a_2	0.54	0.92	0.09	0.64	1.36	0.08	0.52	0.75	0.09
b_3	0.05	-0.24	0.28	0.05	-0.24	0.33	0.04	-0.25	0.27
a_3	0.12	0.25	-0.02	0.11	0.43	-0.04	0.13	0.18	0.01
b_4	1.00	1.24	-0.03	1.05	1.35	0.02	0.94	1.20	-0.06
a_4	0.22	0.20	-0.02	0.24	0.23	-0.04	0.22	0.19	-0.02
b_5	-0.08	-0.09	0.03	-0.07	-0.09	0.05	-0.08	-0.10	0.03
a_5	-0.04	0.04	0.04	-0.04	0.05	0.05	-0.03	0.03	0.03
b_6	0.36	0.38	0.13	0.37	0.40	0.14	0.35	0.37	0.13
a_6	0.06	0.03	0.02	0.07	0.04	0.02	0.05	0.02	0.02
b_7	-0.27	0.10	-0.04	-0.26	0.08	-0.04	-0.26	0.10	-0.04
a_7	-0.16	0.20	0.01	-0.16	0.19	0.01	-0.15	0.20	0.01
b_8	0.84	0.78	0.62	0.85	0.78	0.63	0.84	0.78	0.62
a_8	0.12	0.08	0.06	0.12	0.09	0.07	0.12	0.07	0.06

N.B. b_2, b_4, b_6, b_8 are allowed terms. b_1 may come from feeddown of b_2 and non-centering of mean-coil.

FNAL DATA

Room Temperature Measurements of S cos θ Style Model Magnets at FNAL (Multipoles for 5 cm Dry Wound Coils at 1 cm)

	SG1003		SG1004	SG1006	SK1001	SJ1003
b_1	0.23	±1.5	-1.42	0.069	-2.36	0.26
a_1	-1.89	±2.0	0.69	4.78	-1.30	0.85
b_2	42.98	±0.5	43.44	43.81	15.58	7.16
a_2	0.42	±0.15	1.14	-0.397	-2.06	-0.81
b_3	0.02	±0.10	-0.12	0.115	0.20	0.50
a_3	-0.47	±0.30	0.035	0.422	-0.30	0.82
b_4	2.24	±0.20	2.32	2.30	1.59	-0.20
a_4	0.002	±0.10	-0.040	-0.066	0.116	-0.163
b_5	0.031	±0.05	0.062	-0.007	-0.007	0.042
a_5	0.204	±0.05	0.036	-0.165	0.145	0.015
b_6	-0.456	±0.05	-0.470	-0.433	-0.314	-0.295
a_6	-0.02	±0.02	-0.019	-0.004	-0.007	-0.016
b_8	0.042	±0.05	0.045	0.046	0.014	0.0056
a_8	0.0003	±0.005	0.001	0.0002	-0.0014	0.0031

TAC DATA

Table b_n for TAC001.

B(T)	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
0.01161	17.8	-156.0	24.5	-43.8	7.5	-8.4	2.9	3.9
0.14526	1.9	-0.1	2.1	6.2	0.9	1.4	0.4	-0.5
0.25329	1.3	-0.2	1.2	6.1	0.3	1.8	-0.1	0.8
0.51360	0.6	0.2	1.2	4.8	0.4	1.7	0.4	1.2
1.03262	0.5	-0.4	1.1	5.1	0.7	2.3	0.5	1.3
1.77290	0.1	-0.5	0.4	7.2	0.0	2.9	0.5	0.8
2.53527	0.3	-0.1	0.0	2.2	0.2	2.8	0.3	0.9
2.93804	0.3	0.3	-1.3	-16.7	-0.2	-0.5	0.0	0.7
0.01158	24.5	-156.0	26.0	-51.3	4.0	-12.6	7.8	10.7
0.14570	3.4	-0.7	2.6	5.3	1.5	1.1	1.7	-2.5
0.25401	1.8	0.0	1.0	6.5	0.2	2.4	0.3	0.5
1.03333	0.3	-0.3	0.7	4.6	0.0	2.3	0.0	1.2
1.77397	-0.2	-0.2	0.5	7.4	-0.1	2.5	0.9	-0.2
2.53723	-0.3	0.0	-0.1	2.2	0.4	2.9	0.1	0.8
2.98844	0.5	0.1	-1.3	-17.5	0.1	-0.8	1.2	0.7
0.01170	25.0	-155.6	29.0	-47.6	12.3	-8.4	3.2	4.7
0.14579	3.4	-0.7	2.5	5.6	1.3	0.8	1.5	1.5
0.25364	1.3	-0.2	2.1	5.6	0.9	2.0	0.1	1.5
1.03322	0.5	-0.4	0.9	5.1	0.1	2.1	0.4	1.0

TAC DATA

Table b_n for TAC002.

	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8	b_9
0.01145	-2.4	158.8	0.0	47.6	2.9	-7.8	2.5	11.6	-0.8
0.14473	-0.1	0.3	1.6	5.7	0.5	2.1	-0.2	1.1	-0.3
0.25295	-0.3	-0.4	1.4	4.7	0.7	1.4	0.8	0.4	0.7
0.51206	-0.7	0.9	0.9	5.0	0.3	2.0	0.2	1.3	-0.4
1.03050	-0.5	0.0	1.0	4.9	0.5	2.0	0.1	0.7	-0.1
1.76895	-0.9	-0.7	1.2	6.2	1.0	2.4	0.6	0.7	-0.3
2.53050	-0.7	-1.1	0.4	1.6	0.7	2.7	0.6	0.7	-0.2
2.98316	-0.4	-0.3	-1.8	-17.8	0.1	-0.8	0.0	0.5	0.0
0.01153	4.6	156.3	3.0	46.4	3.0	-8.2	-3.2	-1.1	2.1
0.14481	0.4	0.7	1.3	5.8	1.0	1.3	0.2	0.6	0.1
0.25328	-0.1	-0.2	1.4	5.0	0.8	1.8	0.6	0.4	0.7
0.51199	-0.6	0.9	0.9	5.0	0.7	1.6	0.8	0.1	0.5
1.03036	-0.4	0.0	1.1	4.9	0.5	2.0	0.2	1.0	-0.1
1.76867	-0.7	-0.6	1.0	6.6	0.5	2.9	0.2	1.0	-0.1
2.53047	-0.4	-1.2	0.8	1.3	1.1	2.4	0.6	0.7	-0.1
2.98307	-0.4	-0.5	-1.8	-17.4	0.0	-0.8	0.0	1.0	-0.1
0.01154	-0.1	-156.6	4.8	-45.7	3.6	-10.0	-2.5	6.6	-0.4
0.14468	0.4	0.7	1.9	5.4	0.8	1.6	0.0	0.2	-0.3
0.25290	0.2	0.0	1.4	4.5	1.0	2.0	-0.3	1.0	0.8
0.51190	-0.5	0.9	0.8	5.0	0.7	1.7	0.5	0.4	0.1
1.03032	-0.4	-0.1	1.2	4.5	0.5	2.1	0.1	0.9	0.7
1.76854	-0.6	-0.7	1.2	6.4	0.7	2.8	0.1	1.4	-0.3
2.53060	-0.4	-1.1	0.5	1.6	0.9	3.0	0.1	0.7	0.2
2.98384	-0.7	-0.2	-1.9	-17.4	0.1	-1.0	0.3	0.7	0.3

TAC DATA

Table a_n for TAC001.

$B(T)$	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8
0.01161	-106.7	+4.6	-35.1	-4.0	-0.8	-1.4	-5.4	-3.6
0.14526	-3.5	1.8	-0.8	0.0	0.6	-0.2	-0.2	1.2
0.25329	1.2	0.8	0.5	1.0	-0.2	0.5	0.2	-0.6
0.51360	2.8	1.2	1.0	0.1	0.6	0.1	0.5	0.4
1.03262	4.6	0.4	2.1	0.3	0.9	0.2	0.5	-0.9
1.77290	4.8	0.4	2.1	0.4	0.7	0.7	0.0	0.6
2.53527	3.7	0.3	1.0	0.4	0.6	0.6	0.0	1.0
2.93804	2.4	-0.2	-2.2	-0.5	-0.3	0.3	-0.6	0.8
0.01153	-151.8	6.6	-49.2	-6.4	-6.0	-5.3	+2.2	-4.3
0.14570	-5.6	1.1	-0.3	-0.7	-0.2	1.9	0.6	-2.3
0.25401	-0.2	0.9	0.4	0.8	0.7	1.2	-0.2	-1.0
1.03333	3.9	0.8	1.8	0.0	0.9	0.3	0.5	0.3
1.77397	4.5	0.9	1.8	0.8	0.2	1.1	-0.2	0.9
2.53723	3.2	0.5	0.5	0.4	0.5	0.8	-0.3	0.6
2.98844	2.6	-0.2	-1.9	-1.0	-0.4	-0.4	0.4	0.3
0.01170	-162.3	0.0	-53.7	-3.7	-7.4	0.0	0.7	2.8
0.14579	-5.6	1.1	-2.1	-0.1	-0.3	-0.9	2.4	-1.7
0.25364	-1.6	1.0	0.1	0.2	0.9	0.7	-0.8	0.5
1.03322	3.7	0.7	1.6	0.0	0.7	0.3	0.2	0.1

Table a_n for TAC002.

	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9
0.01145	27.0	-16.7	11.6	-5.2	2.7	1.8	5.4	0.8	-0.4
0.14473	-2.7	-2.1	-2.1	-0.5	-0.9	-0.4	-0.3	-0.4	0.2
0.25295	-3.3	-1.7	-1.8	0.3	-0.8	-0.4	-0.4	0.3	-0.6
0.51206	-3.4	-1.4	-2.0	-0.2	-0.7	-0.2	-0.1	-0.3	0.0
1.03050	-3.8	-1.3	-2.1	0.1	-0.6	-0.1	0.2	-0.4	0.1
1.76895	-3.8	-1.4	-2.7	0.5	-1.2	0.0	-0.3	-0.9	0.6
2.53050	-3.5	-1.1	-1.4	0.0	-1.2	-0.2	-0.3	-0.5	0.4
2.98316	-2.7	-0.6	3.1	-0.8	0.4	-0.2	0.2	-0.3	0.1
0.01153	31.7	-18.6	15.9	-4.7	3.5	2.8	-1.4	5.6	0.3
0.14481	-2.9	-2.1	-2.4	0.2	-0.7	-0.7	-0.5	0.5	0.0
0.25328	-3.0	-1.3	-2.1	-0.2	-0.8	0.0	-0.4	-0.2	-0.5
0.51199	-3.7	-1.3	-2.1	-0.2	-0.6	0.0	-0.1	-0.4	-0.3
1.03036	-3.5	-1.3	-2.1	-0.1	-0.7	0.0	-0.3	-0.3	0.4
1.76867	-3.6	-1.3	-2.5	-0.1	-1.0	0.1	-0.6	-0.1	0.0
2.53047	-3.2	-1.2	-1.3	0.1	-1.2	0.3	-0.5	-0.4	0.5
2.98307	-2.5	-0.8	3.2	-0.9	0.4	-0.1	-0.1	-0.8	0.3
0.01754	39.3	-18.7	19.2	-3.2	-0.8	5.5	0.8	-3.6	0.3
0.14468	-2.1	-2.0	-2.5	-0.2	-0.5	0.0	-0.3	0.1	0.3
0.25290	-2.7	-1.6	-1.7	0.2	-0.7	-0.2	-0.3	0.1	0.3
0.51190	-3.4	-1.4	-1.8	-0.2	-0.5	-0.1	0.1	-0.6	0.3
1.03032	-3.5	-1.2	-2.0	0.0	-0.8	0.1	-0.4	-0.2	0.1
1.76854	-3.5	-1.7	-2.3	0.1	-1.0	0.0	-0.8	0.0	-0.1
2.53060	-3.4	-1.1	-1.2	-0.1	-1.0	0.2	0.1	-0.7	0.3
2.98384	-2.8	-0.5	3.0	-0.4	0.2	-0.3	0.0	-0.5	0.4

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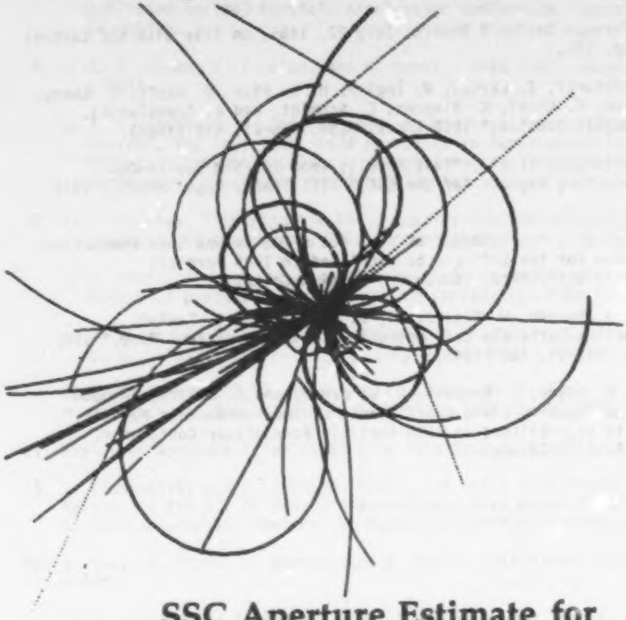
APPENDIX 7

SSC-SR-1013

The Superconducting Super Collider



SSC Aperture Estimate for Cost Comparisons

Aperture Task Force

August 9, 1985

The optimal parameters listed in Eqs. (23) and (24) should be changed to

$$d_c = 4.1 \text{ cm}, \quad L = 155 \text{ m} \quad \text{for Design C} \qquad (23)$$

$$\begin{aligned} d_c &= 5.0 \text{ cm}, \quad L = 140 \text{ m} \quad \text{for Design C} \\ d_c &= 4.7 \text{ cm}, \quad L = 90 \text{ m} \quad \text{for Design D} \end{aligned} \qquad (24)$$

These changes do not affect the costs or any other conclusions contained in the paper.

SSC Aperture Estimate for Cost Comparison

Aperture Task Force, August 9, 1985

Edited by A.Chao and R.Talman

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I. INTRODUCTION

One of the inputs to making a cost comparison between different magnet designs is the physical size of the magnet coils. To minimize the cost of the magnets, the coil size must be minimized.

The coil size on the other hand must be large enough to allow

- good field quality for the single particle motion to be stable within a certain needed aperture.
- the vacuum pipe wall to be sufficiently away from the beam to avoid collective instability effects.

The main limitation on coil size is found to be imposed by the single particle dynamics. The multipole field errors increase as the coil size is reduced. At a certain point the field quality becomes intolerable for single particle stability. In this report an algorithm is developed to find the minimum acceptable coil size which, combined with magnet specification and cost information, leads to the minimum magnet cost. Chapters II-V describe the details of this cost minimization procedure according to the single particle stability criterion.

Chapter VI briefly discusses the aperture considerations imposed by the collective effects. It is shown that, for the cases considered, the collective effects do not impose important limitations on the coil size except for one case which may be operating close to the instability margin.

For the single particle dynamics considerations, we have included in this report the results for one cosine (the D type) magnet and one superferric (the C type) magnet. For the studies of collective effects, we have included a high-field (6 Tesla) case and a low-field (3 Tesla) case.

II. BASES FOR ESTIMATING

There are basically four inputs to the coil size determination discussed in this report: the aperture requirements, the magnet field multipole errors, the lattices, and the unit cost information. In this chapter, we will describe these inputs in sections 2.1-2.4 and the algorithm of how to derive the optimal coil size from these inputs in section 2.5.

2.1 Aperture Requirements

Enough aperture must be provided for beam injection, operation, and storage purposes. We have identified two grades of apertures: the "linear aperture" and the "dynamic aperture." Within the linear aperture the particle motion is basically linear (with a certain tolerance on linearity); it represents the high grade aperture needed for routine beam operations, allowing for normal pulse-to-pulse variations. At the dynamic aperture limit, the particle motion is still stable but not necessarily linear. The beam therefore stays in the vacuum pipe, allowing for valuable diagnosis, trouble shooting, and safe abort to be made, but the detailed beam behavior may not be easy to understand and beam emittance may no longer be suitable for high luminosity runs after such operation.

The criteria we use to define the linear aperture are

- the "smear"[1] of the linear invariant due to nonlinearities does not exceed an rms of 10%.
- the horizontal and the vertical tune shifts with amplitude (on-momentum) do not exceed 0.005.[1]

If, at a certain amplitude, either of the above criteria is reached, this amplitude will be designated as the linear aperture. Smear and tune shifts are the quantities chosen to quantity the nonlinearities in the storage ring. The proposed numbers (10% for smear and 0.005 for tune shifts) are applied uniformly to all magnet types for making cost comparisons. While these criteria are based on past accelerator experience, further studies including experiments at the Tevatron will be pursued to check their accuracy.

The needed linear aperture is a function of lattice design. In this report we have restricted ourselves to those lattices with 60° phase advance per cell in the arcs since they are thought to have the best achromatic behavior in the absence of magnet errors. The needed aperture is studied as a function of only the cell length of the lattice.

In this report, when a value of linear aperture or dynamic aperture is mentioned, it represents the total deviation from the design trajectory in both the horizontal and vertical directions. A particle with 1.414 mm linear aperture therefore indicates that the motion with simultaneously 1 mm amplitude in x (at maximum β_x in the cells) and 1 mm amplitude in y (at maximum β_y in the cells) is basically linear.

Operational experience with the Tevatron at FNAL has influenced the estimate of the needed aperture. Table 1 is an itemized list of the linear aperture needs for a lattice with β_{max} = 300 m in the cells estimated (with slight modifications) in Ref.2.

Table 1. Itemized List of Linear Aperture Needs Estimated and Scaled From Tevatron Operations Experience.

	Need	Estimated Value
x_1	residual betatron oscillations	±1.5 mm
x_2	beam betatron size (95%)	±1.3 mm
x_3	closed orbit errors	±1.25 mm
x_4	kicker waveform variations	±0.1 mm
x_5	miscellaneous effects on betatron motion	±0.5 mm

Included in x_5 are miscellaneous effects[2] such as power supply ripple, lattice mismatch, lattice non-uniformities, etc. When the half-cell length L is varied, the components x_1, x_2, x_4, and x_5, are scaled by $(\beta_{max}/300\ m)^{1/2}$. We have assumed that the closed orbit error x_3 is independent of β_{max}, being dominated by beam position monitoring and control system errors. To obtain the total needed linear aperture, we add the above components involving betatron motion.

$$A_{linear} = [x_1{}^2 + x_3{}^2 + x_4{}^2 + x_5{}^2]^{1/2} + x_2 \qquad (1)$$

Equation (1) represents the needed linear aperture for on-momentum particles. The result as a function of L is shown in Fig. 1. A numerical fit, which will be used, later, to this functional dependence is

$$A_{linear}(mm) = 0.934\ [L(m)]^{0.36}. \qquad (2)$$

As mentioned previously, in addition to the linear aperture requirement, there is the need for a lower-grade dynamic aperture for diagnosis, trouble shooting and safe abort purposes and for room needed for occasional bad injections. It is important that the achieved dynamic aperture be substantially greater than the linear aperture. It is the linear aperture, however, that is regarded as the prime requirement to be imposed on our aperture evaluation. In this report, we will make an attempt to obtain the dynamic aperture (section 5.3) and show it is substantially larger than the linear aperture. We do not address the question of how to utilize the surplus aperture effectively.

The aperture need relaxes substantially after injection. This report has therefore considered only the case at injection. The beam energy is taken to be 1 TeV and the beam emittance $\epsilon_x = \sigma_x\sigma_{x'} = 1.0\text{x}10^{-9}$ m-rad and $\epsilon_x = \epsilon_y$. The needed aperture does not depend sensitively on the injection energy in the estimates above because most of the components of the needed aperture

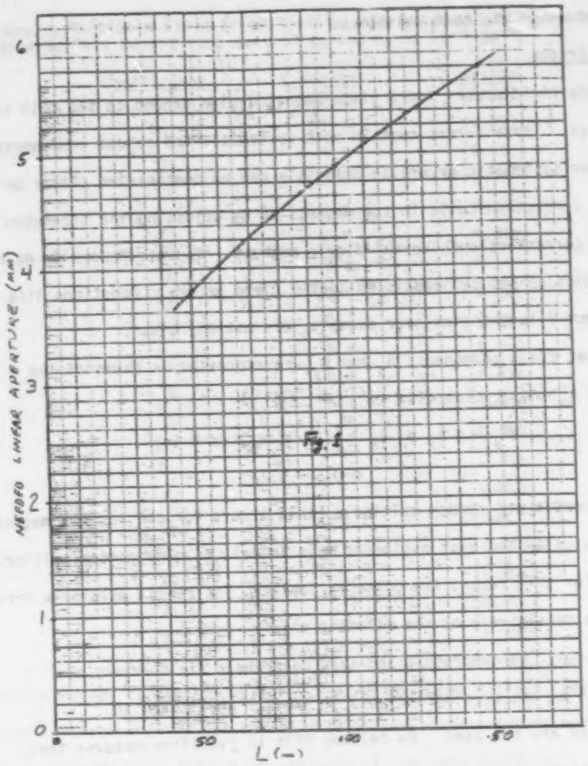

Fig. 1. Estimate of the needed linear aperture as a function of half-cell length L. The same curve applies to both low and high field designs.

are independent of the beam emittance.

2.2 Magnet Errors

Multipole field errors for a given magnet design depend on the coil size of the design. These errors contain both systematic and random components. The low order systematic errors in principle can be compensated either by distributed correction coils in the magnets or by adjusting the strengths of some lumped correctors outside the dipole magnets. In this report we do not include studies of the systematic multipole field errors. Questions like what is the optimum filament size, for example, are not addressed.

The magnet field components B_x and B_y are expressed in terms of the coefficients a_n and b_n according to

$$B_y + i\,B_x = B_o \sum_{n=0}^{\infty} (b_n + ia_n)\,(x + iy)^n. \tag{3}$$

The systematic and random multipole field errors for the various magnet designs are studied and best estimates made in Ref. 4. The random multipole values used for this report are given in Table 2. The random multipole errors do not depend sensitively on the filament size.

In this study, no quadrupole and skew quadrupole field errors are included. The a_1 and b_1 coeffiecients in Table 2 are listed in parentheses and are not used. We believe this is justified because these linear error effects can be compensated for relatively simply by the quadrupole and skew quadrupole correction coils in the spool pieces. It may be necessary to reserve sorting[5] of magnet positions to further reduce the effects. Also, we have not included the orbit error effects caused by a_0 and b_0 (other than including an orbit contribution in the estimate of the needed apertures) as they will be corrected by steering elements.

Table 2. Random Multipole Field Error Coefficients for C and D Magnet Designs Used in This Report (the unit of a_n and b_n is 10^{-4} cm^{-n}).

Coefficient	C design	D design
a_1	(3.1)	(0.72)
b_1	(1.2)	(0.72)
a_2	1.1	0.63
b_2	1.0	2.15
a_3	1.3	0.69
b_3	0.8	0.35
a_4	0.8	0.14
b_4	0.4	0.59
a_5	0.7	0.16
b_5	0.4	0.059
a_6	0.7	0.034
b_6	0.5	0.076
a_7		0.030
b_7		0.016
a_8		0.0064
b_8		0.021
a_9		0.0056
b_9		0.0030
a_{10}		0.0012
b_{10}		0.0071

The random magnet errors for Design D are derived from a study[4] based on the existing Tevatron and the CBA magnet data. These data are then scaled to the SSC design interpreted through an analysis of the sensitivity of multipoles to various coil placement and current errors. The random magnet errors for Design C are derived partly from the first measurements made on 6 model magnets and partly from preliminary sensitivity analyses.

More statistics are being gathered and more sensitivity analyses made on the magnet designs. Further information should be available at the end of August, 1985.

In the studies presented here, only single-channel magnets are considered. Because only random errors enter these considerations, C is taken as representative of all superferric variants and D of all cosine theta variants.

We will report on some results when the magnets are sorted. The sorting scheme used in this study is a rudimentary one which attempts to minimize only the effects of the b_2 field errors. In this sorting scheme, the number of magnets being sorted corresponds to 2π betatron phase advance. Sorting is then performed on these magnets according to the scheme illustrated in Fig. 2. This is then repeated for the next number of magnets until all magnets in the ring are exhausted. (Lindsay Schachinger)

For all tracking results in this report the lengths of individual dipole magnet units have been held approximately constant. That is, 6 Tesla magnets are about 17 m long and 3 Tesla magnets are about 32 m long. In the future, it will be important to optimize this parameter taking into account the improvement resulting from a sound sorting scheme.

2.3 Test Lattices

For a given magnet design, and thus its field errors, the aperture depends on the lattice of the storage ring. Five test lattices used in this study are

Lattice	L(m)	μ	β_{max} in cell (m)	$\nu_x \approx \nu_y$	B_0(Tesla)
FODO	variable	60°	variable	80.19	variable
C1	145	60°	502	106.28	3
C1S	72.5	60°	251	232.28	3
D1	100	60°	346	85.28	6
D1S	50	60°	173	220.28	6

The first π phase advance:

[+1 -1 +3 -3 +5 -5 ....]

The second π phase advance:

[+2 -2 +4 -4 +6 -6 ....]

The third π phase advance:

[-1 +1 -3 +3 -5 +5 ....]

The fourth π phase advance:

[-2 +2 -4 +4 -6 +6 ....]

Fig. 2. The sorting scheme used in this report. The index +1 means the member that has the most positive b_2 among the group of magnets being sorted, -1 means the most negative, etc. Magnets in the 5th π advance will be ordered the same way as the first π.

The FODO lattice is used to expedite the calculations (see Chapter IV). It consists of nothing but FODO cells with variable cell length and is used for either C or D designs. The other four lattices[6] contain interaction regions. In all cases, the betatron phase advance per cell is $\mu = 60°$ and two families of sextupole are inserted in the arcs cells to correct for the chromaticities. The bending field strengths are 3 and 6 Tesla at 20 TeV for C and D magnet designs, respectively. The betatron tunes are chosen so that no pronounced resonance effects are observed. As we will see, one emphasis of these lattices will be the study of the dependence of linear aperture on the cell length.

2.4 Unit Costs

In order to understand the cost implications of choosing a coil diameter, d_c, and a half-cell length, L, we have devised a cost estimating model (Peter Limon, Don Edwards) as a function of these parameters. The model yields costs relative to a base which is derived from the estimates made by CDG of a "standard" SSC built from each of the magnet types.

The model used assumes that the total cost of the collider rings is the sum of the tunnel cost, plus the technical components. For simplicity, we ignore all technical components other than the magnets. It is important to note that the "cost" that result from this model is not the total cost of the machine. It does not include contingency EDI&A, technical components other than magnets or conventional construction. Then

$$\text{total cost} = V = \text{tunnel cost} + \text{dipole cost} + \text{quadrupole cost} + \text{spool cost}. \quad (4)$$

If the number of half cells is N and the effective bend length per half cell is L_B, then

$$V = NLT + kN\,(L_B D + Q + S), \quad (5)$$

where

L = half cell length
T = tunnel cost per meter
D = dipole cost per meter
Q = quadrupole cost per unit
S = spool piece cost per unit
k = 1 for 2-in-1 types and 2 for 1-in-1 types.

Since $N = 2\pi\rho/L_B$, the cost per meter of bend is given by

$$v = V/2\pi\rho = LT/L_B + kD + k(Q+S)/L_B. \quad (6)$$

The bend length L_B can be calculated once one knows the lengths of the devices and interfaces between the devices, i.e.,

$$L_B = L - \ell_{quad} - \ell_{spool} - \ell_m - L_I. \quad (7)$$

For the model, we assume

ℓ_s = spool length = constant
ℓ_m = miscellaneous gaps (e.g., beam detectors) = constant
L_i = total interface length = $n_o \ell_i L/L_o$
ℓ_i = length per interface
L_o = reference half cell length
n_o = reference number of dipoles per half cell
ℓ_q = quadrupole length = $\ell_{qo} L_o/L$.

The quadrupole length is scaled from its reference length d_{qo} to maintain a constant betatron phase advance per cell (60°) and a constant quadrupole gradient (130 T/m for D design and 90 T/m for C design).

The reference values for the unit costs used in the model are obtained from the cost estimates for each magnet type, either from the RDS[3] or from later compilations.

Quadrupole Cost Per Unit

$$Q = Q_o + (L_o/L)\,[Q_{o1} + Q_{11}\,(d/d_o) + Q_{21}\,(d/d_o)^2] \qquad (8)$$

where d is the coil inner diameter and d_o is its reference value. It has been assumed that the amount of superconductor needed for a constant gradient quadrupole scales as d^2. The cost of the lamination steel varies as the square of the outer steel diameter with no relation to the coil diameter.

Dipole Cost Per Meter

$$D = D_o + D_1\,(d/d_o) + D_2\,(d/d_o)^2. \qquad (9)$$

D_1 is dominated by the cable cost. Coil winding labor also varies linearly with coil diameter. D_o includes installation and magnet stands. D_2 represents the iron material cost.

Tunnel Cost

From the RDS, for a 90 km tunnel, the parts that scale with tunnel length are

\$ 336 M	tunnel
15 M	land improvements
38 M	utility distribution
\$ 389 M	total, or \$ 4.32K/meter.

The same tunnel cost per meter is used for both magnet designs.

Substituting these into Eq.(6) and for the D design with 6.4 tesla field, we take

	Units	D	C
L_o	m	100	120
ℓ_{qo}	m	5	6.5
ℓ_s	m	6.2	6.5
ℓ_m	m	2.7	1.5
ℓ_1	m	0.9	0.25
n_o	-	4	2
S	K\$	36.8	80.0
D_o	K\$/m	1.73	0.68
D_1	K\$/m	3.48	1.15
D_2	K\$/m	0	0.32
Q_o	K\$	12.1	6.19
Q_{o1}	K\$	5.6	3.7
Q_{11}	K\$	5.8	3.95
Q_{21}	K\$	9.7	5.44
k	-	2	1
d_o	cm	4	4

We obtain the cost per meter of bending v as a function of coil inner diameter d_c and half-cell length L as shown in Figs. 3 and 4 for designs C and D respectively. The curves are labelled with costs per meter of bending magnet. In comparing C and D designs, since the magnetic fields are in the ratio of 2 to 1, it is accurate to mentally divide the values on Fig. 4 by a factor of 2 for comparing with the values on Fig. 3 as regards the total cost.

Figure 5 gives the dipole filling factor, i.e., the fraction of the arc region that is occupied by dipoles, for the C and the D designs as a function

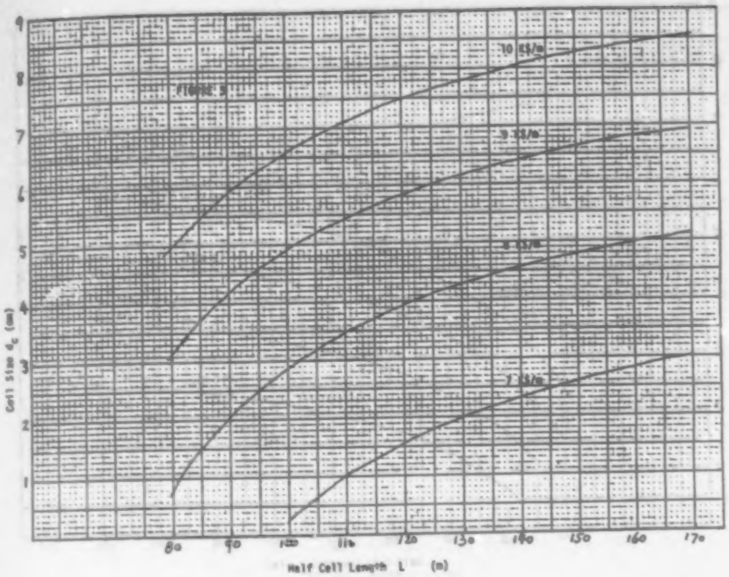

Fig. 3. Contours of constant cost in the (d_c, L) plane for the C magnet design. The cost estimate takes into account the tunnel, the quadrupole and dipole magnets, and the spool pieces.

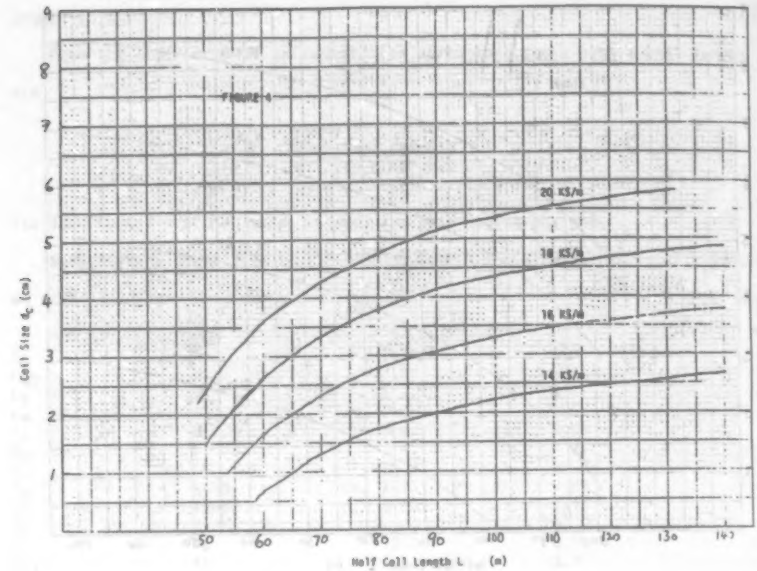

Fig. 4. Same as Fig. 3 for magnet design D.

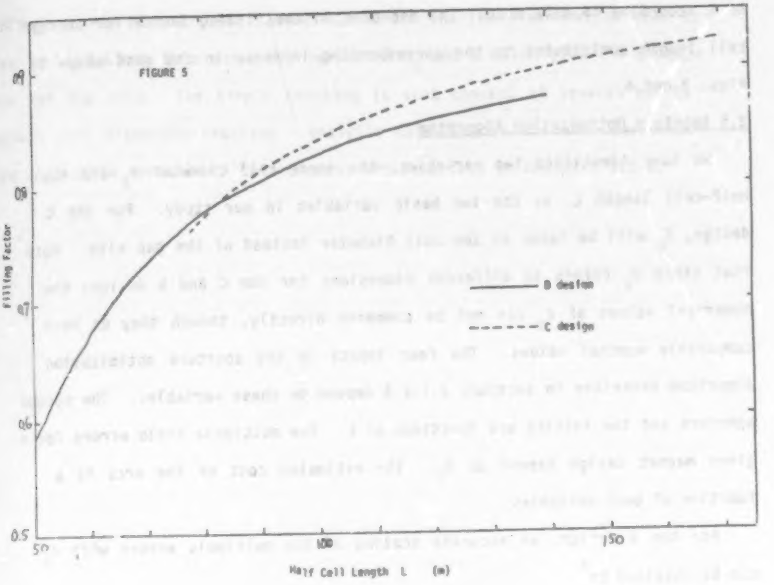

Fig. 5. Dipole filling factor vs L for C and D magnet designs.

of L according to this model. The decrease in the filling factor for shorter cell length contributes to the corresponding increase in the cost shown in Figs. 3 and 4.

2.5 Aperture Optimization Algorithm

We have identified two variables, the inner coil diameter d_c and the half-cell length L, as the two basic variables in our study. For the C design, d_c will be taken as the coil diameter instead of the gap size. Note that since d_c refers to different dimensions for the C and D designs the numerical values of d_c can not be compared directly, though they do have comparable nominal values. The four inputs to the aperture optimization algorithm described in sections 2.1-2.4 depend on these variables. The needed aperture and the lattice are functions of L. The multipole field errors for a given magnet design depend on d_c. The estimated cost of the arcs is a function of both variables.

For the D design, an accurate scaling of the multipole errors with d_c can be obtained by[4]

$$a_n, b_n = d_c^{-n-1/2} \tag{10}$$

From Table 2, which lists the multipole values for $d_c = 4$ cm, the random multipoles for different values of d_c can be obtained. For the C magnet, the scaling with d_c is less certain, but we have carried out the study using Eq.(10) as a model. Results are therefore less reliable when d_c deviates too much from 4 cm.

The algorithm is the following: For given d_c and L, the lattice and the multipole errors are specified. We first use a simplified tracking program to find the linear aperture achieved using these inputs. If the achieved aperture is less than the needed one, this combination of (d_c, L) is not acceptable. Exploring the (d_c, L) plane then gives a curve on which the achieved aperture equals the needed aperture. The cost information then is used to find along this curve the values of d_c and L which give the minimum cost for the arcs. The simple tracking is spot checked at several points against more elaborate tracking. Analytic calculations are also performed when applicable. Details of this process are described in Chapters III-V.

TASK GROUP S3.3. - MUCK RECEIVING & SEPARATION

Objectives - To design a muck surface-receiving system for the muck as it is ejected through the service hole casing. The muck may, however, have to be separated from the water added at the concrete pump. The design rate will be 415 tons/hour. The system must be portable with a very short set-up time and require no more than two operators.

Background - Cyclones have been used for years to separate particulates from both water and air streams. Vibrating shale shakers have also been used for years to separate coarse sand size materials from mud drilling fluids. The technology of cyclones and vibrating screens is well advanced. Also, large portable mud tanks have been used in the oil industry. They are used to hold the colloidal mud slurry for return to the drill hole.

The muck will be injected into a portable cyclone, which will also serve as a bottom-dump hopper. The water and fines will be taken off the top and pumped to a vibrating shale shaker mounted on top of the portable mud tank. The cyclone will allow the muck to be dropped into dump trucks to be hauled to a fill site. The material from the shale shaker will be similarly handled. The very fine cuttings can be pumped out of the mud tank into tankers to be hauled to sludge-drying beds. The decanted water can be pumped back downhole to the muck-fluidizing hopper. Makeup water can be added to the mud tank as needed. The muck-receiving system is shown in Figure A8.

Planned Approach to Meeting Objectives - Various manufacturers of mining and oilfield equipment, such as Dresser Company and Ingersoll-Rand Company, have been contacted. Both have volunteered their help and advice. Other companies will also be contacted so as to design the most efficient and reliable muck-receiving system.

The surface handling of the muck will depend upon soil type, water content, and site surface requirements. A cost-minimum approach would be simply to landscape it at each surface penetration to form a hill, thus eliminating need for separation or haulage.

TASK GROUP S4.1. - SURFACE SERVICE COMPONENTS

Task S4.1.1. Objective - To design a portable surface blower system to ventilate the tunnel heading, the muck lift zone, and the tunnel lining system zone.

Background - A minimum of 20 cfm/ft^2 of tunnel face or 200 cfm/man is required for tunnel ventilation. The blowers or compressor, according to OSHA specification, must be powered by dual sources such as an electric motor and a diesel engine. The ventilation air will be pumped down one of the cased 12-inch service holes and then through a duct carried on the bottom of the trailing conveyor belt.

Planned Approach to Meeting Objective - The design of the ventilation system will not require any new developments. Bonanza, Joy, Dresser, Ingersoll-Rand, and other companies manufacture vane/axial fans that will be adequate. Other manufacturers will be contacted to determine the best system. Typically, a 10,000 cfm fan operating against a head of 2.5 inches of water can ventilate a tunnel of 10-ft diameter 6 miles long. The air return will be down the tunnel to vent at surface service holes not being used to the inclined ramp portals.

Task S4.1.2. Objective - To design or select a portable compressed air unit to pump air down a hose hanging in the ventilation duct to the muck air lift.

Background - About 1 cfm is required for each pound of muck. Since the maximum anticipated shaft depth is 400 ft, the maximum air pressure will be about 400 psi. For 415 tons of muck per hour, about 14,000 cfm will be required.

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Planned Approach to Meeting Objective - The design of the compressed-air system will require no new developments. Atlas Copco-Jarva, Denver-Gardner, Joy, and other companies build units that can serve this purpose. These and other companies will be contacted to help select the most efficient and reliable unit for the lowest cost. Hoses and hose connections will also be a part of this portable electric unit.

Task S4.1.3. Objective - To design or select a pump to circulate the water for muck fluidization.

Background - About 15% water will be required to fluidize the muck to get it to enter the concrete pump. In order to pump 415 tons/hour, roughly 200 gals per minute will be required at a pressure of no more than 50 psi. The elevation difference between the surface and the tunnel will also supply extra pressure.

Planned Approach to Meeting Objective - The design of water or mud pumps will not involve any new development. One of the best pumps for water carrying abrasive particles is the Moyno pump manufactured by the Robbins Myers Company, Springfield, Ohio. The male helix rotor is stainless steel and the female stator is cutless rubber with twice the pitch of the rotor. This company, along with other companies that make water/mud pumps, will be contacted in order to select the most efficient pump for the lowest cost. It will be electrically driven.

Task S4.1.4. Objective - To design a portable switching and transformer system to connect an overhead power line to the tunneling equipment.

Background - The power source for the tunneling equipment will be an overhead power line that will follow the route of the tunnel. Roughly

1,500 hp is required to drive the TBM and the muck-handling system. This will be supplied through an insulated cable dropped down through the current ventilation service hole. At the tunnel, the power will be split to supply both the muck-handling system and the tunnel boring machine. The power to the TBM will also supply the belt conveyor.

Planned Approach to Meeting Objective - Many companies such as General Electric and Westinghouse manufacture the switches, circuit breakers, transformers, and insulated cables necessary to tap the overhead power line and transmit the power through the service holes to the tunneling equipment. These and other companies will be contacted so as to select the most efficient and reliable equipment for the lowest cost.

TASK GROUP S5.1. - CONCRETE MIXING & CONVEYING

Objectives - To design or select a portable concrete batch plant with pumps and hose to be located at the service holes. The concrete will be conveyed down the service holes through a hose to either a shotcrete robot or to the slip forms which will be used to line the tunnel. The required rate of production is 40 cu yds per hour. This is 150% of the rate required to maintain 1,000 ft per day of 6-inch lining.

Background - The longer concrete is mixed and the higher the water content, the lower the strength. To get good quality control with low mixing times, it seems that site batching is required. Dry-blended concrete can be pumped in a hose by using air as the conveying fluid just as gunite is conveyed. This system has the advantage that water can be added just before the concrete is sprayed on the wall as shotcrete or injected into forms. The disadvantage is that the process is energy inefficient and it is difficult to maintain a constant water content. Wet concrete can also be pumped if it has sufficient water. The advantage is that the process is energy efficient and the water content can be controlled. The disadvantage is that much water is required and the water must be mixed in before the pumping begins. The third system combines air and wet concrete so that the concrete moves as slugs separated by expanding slugs of compressed air. This system is more energy efficient than the gunite process. Less water is required and its content can be controlled. The disadvantage is that the water must be mixed in before pumping begins.

Planned Approach to Meeting Objectives - The Barber-Green Company of Aurora, Illinois manufactures a truck-mounted batch plant that can carry 12 cu yds of concrete materials that can be screw mixed as required. It is called a "Concrete-Mobile." It can produce concrete at a maximum rate of 60 cu yds per hour. It is used extensively in bridge and highway work. They have been contacted and they have offered advice, help, and counsel for the project. Schwing America, White Bear, Minnesota, that markets an excellent German concrete pump, has been contacted and they have offered free use of equipment for studies. Shotcrete Plus of Euless, Texas markets the Swiss Laich shotcrete equipment and has also offered help and advice.

Before the final design for a concrete conveyance system can be completed, extensive laboratory tests must be accomplished to find the best and most efficient method. Other companies like Hercules and Challenge will be contacted also. The surface concrete batch plant and tunnel slip-form system is shown in Figure A9.

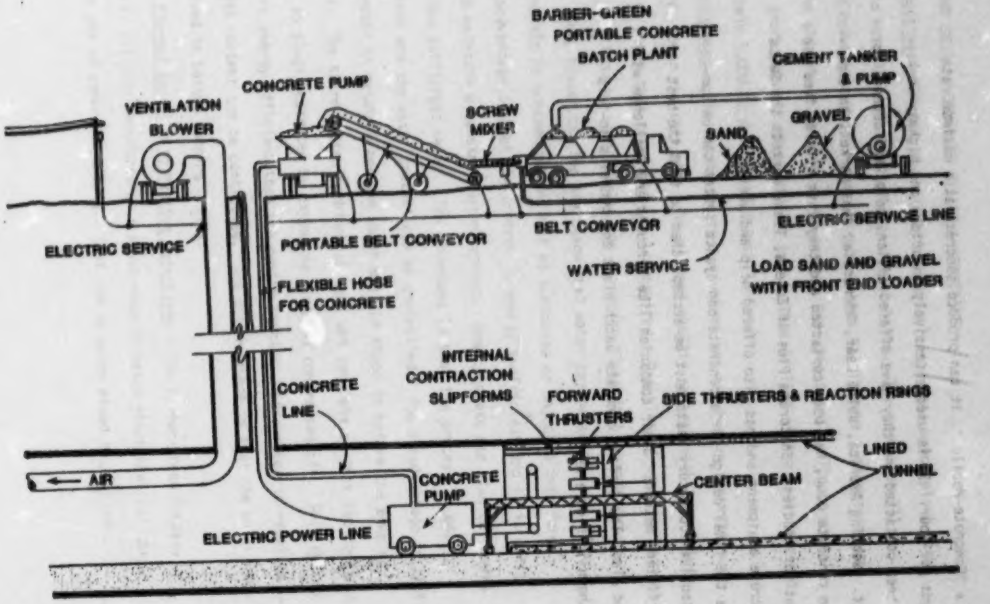
BARBER-GREEN PORTABLE CONCRETE BATCH PLANT
CEMENT TANKER & PUMP
CONCRETE PUMP
VENTILATION BLOWER
SCREW MIXER
SAND
GRAVEL
ELECTRIC SERVICE
PORTABLE BELT CONVEYOR
BELT CONVEYOR
ELECTRIC SERVICE LINE
WATER SERVICE
LOAD SAND AND GRAVEL WITH FRONT END LOADER
FLEXIBLE HOSE FOR CONCRETE
INTERNAL CONTRACTION SLIPFORMS
FORWARD THRUSTERS
SIDE THRUSTERS & REACTION RINGS
CONCRETE LINE
LINED TUNNEL
CONCRETE PUMP
CENTER BEAM
AIR
ELECTRIC POWER LINE

Figure A9. Surface Concrete Batch Plant and Tunnel Slip Form System.

TASK GROUP S5.2. - GROUTING

Objectives - To select the necessary equipment to batch a wide range of grouts to stabilize fractured rock and porous sands and gravels, and to hydrofracture and stabilize soft, impermeable materials such as silty sands and clayey sands. The design rate is estimated to be about 30 gal/min and the maximum injection pressure 1,000 psi. The system is to be portable and self loading as sand, cement, fly ash, lime, bentonite, etc. is dumped at the injection site.

Background - There is an extensive literature on grouting (G2). Grouting can be used to fill the pores in sand and gravel and to fill fractures in cracks and joints in rock. Usually the purpose is to solidify the ground to increase its strength and stiffness and to decrease its permeability.

In impermeable materials the ground around the grout hole can be expanded until the formation is squeezed to the point that it fractures. With continued pumping, the fractures can be filled with grout so that when the grout solidifies, there is a fabric of hard, strong material surrounding pods of the soft, in-place material. A similar technique is used in the oilfield to fracture rock so that sand may be pumped into the fractures. The sand props open the fractures and increases the permeability of the formation. As much as 500,000 barrels of fluid has been pumped into a formation of very limited thickness. The cracks are said to propagate more than one-half mile. Typically, the fracture pressure is roughly 0.8 of the overburden stress. Another grouting technique uses a rotating jet revolving around the injection pipe to penetrate the formation horizontally and to mix the grout with soft silts and sands to form a wide, impermeable mass of cemented soil.

Planned Approach to Meeting Objectives - The French company, Soletanche, has been contacted and its literature obtained. The company is worldwide and has developed some of the most innovative grouting techniques for tunnels and dams. Their "Tube a Manchette" method is world famous. It involves grouting a perforated plastic tube in place in the grout hole. A hollow probe with packers is inserted into the plastic tube and grout is pumped through the plastic pipe perforations. The outside grout is fractured as the surrounding ground is fractured and cemented. An important part of the approach is that the plastic pipe remains open for further grouting, and even for testing the formation.

The Del Val Company, Inc., Fort Worth, Texas, which represents the Hany Grouting System of Switzerland, has also been contacted and it has offered to furnish grout-mixing machines and grout-injecting pumps for tests at no cost. The Halliburton Company has offered its help with hole-casing cementing and all concrete and shotcrete pumping problems. Other companies and consultants such as Hayward Baker, Odenton, Maryland will also be contacted. The Chemical Grouting Company of Japan will be contacted. It has developed the soil-solidification methods involving the super-high pressure liquid jets. After all these data are assembled, trials will be made and the mixing plant, pumps, and injection probes selected to give the most efficient job at the lowest cost for the major conditions expected.

TASK GROUP S5.3. - CONCRETE MIX DESIGN

Objectives - To develop a cost-effective concrete mix that will set up quickly after it is pumped into the tunnel slip forms, a cost-effective shotcrete mix that will set up quickly after it is sprayed on the tunnel walls, and various kinds of cost-effective grouts to stabilize sands, gravels, fractured and jointed rock, karstified rock, and soft, low-permeability silts and clays.

Background - In order to speed the tunnel slip-forming operation and cut down the length of slip forms needed, high early strength concrete is needed. The shotcrete operation will be speeded with rapid-set cement. The concrete mix design will depend to a large extent on how the concrete is pumped from the surface to the point of application in the tunnel. If only the constituent materials are pneumatically delivered to a mixer in the tunnel, any of the fast-set cements listed on page 56 of the original CUTS proposal can be used. If the materials are dry mixed at the surface and pneumatically delivered to the tunnel slip forms or to the shotcrete robot, then only water and an accelerator can be added before spraying or injecting. If the wet concrete is delivered to the tunnel, then the accelerators can be added just before injection or spraying.

Planned Approach to Meeting Objectives - The procedures to be followed in the survey, selection, investigation, characterization, and evaluation of candidate materials for concrete, shotcrete, and various grout materials will be similar to those given in the original CUTS proposal on page 54 - Task Group 2.3. - Concrete Mix.

TASK GROUP S5.4 - SLIP FORMING

Objectives - To design a self-propelled, tunnel slip form that will support freshly injected concrete until it reaches sufficient strength to support itself. The design speed is 1,000 ft per day. It is also required to select a shotcrete robot to move at a similar speed. Both machines are to construct a 6-inch tunnel lining of concrete. Each machine is to include pumps as needed for the tunnel operation.

Background - The background for these tasks is similar to that given for Task Group 3.2. - Slip Forms, page 61 in the original CUTS proposal, with the exception that these slip forms are decoupled from the tunnel boring machine. Shotcrete will be used in the harder sedimentary rocks for the tunnel, such as limestone, and the slip-formed concrete lining will be used in the softer sedimentary rocks, such as shale, stiff clays, and lightly cemented sandstones. In zones originally grouted, the slip-formed concrete lining will also be used.

Planned Approach to Meeting Objectives - The approach for this effort will be similar to the approach given for Task Group 3.2. - Slip Forms, on page 63 of the original CUTS proposal. Since the slip-forming operation is decoupled from the boring operation, the forms must be self propelled. The scheme for accomplishing this is shown in Figure A10, Self-Propelled Tunnel Slip Forms; Figure A11, Tunnel Cross Secton at Spider A; and Figure A12, Tunnel Cross Section at Spider B. The unit will be collapsible so that if it binds up it can be broken down and moved forward. There have been visits to both Blaw-Knox Company, Pittsburgh, Pennsylvania and Burke Company, San Antonio, Texas. These firms are major suppliers of tunnel forms. Each

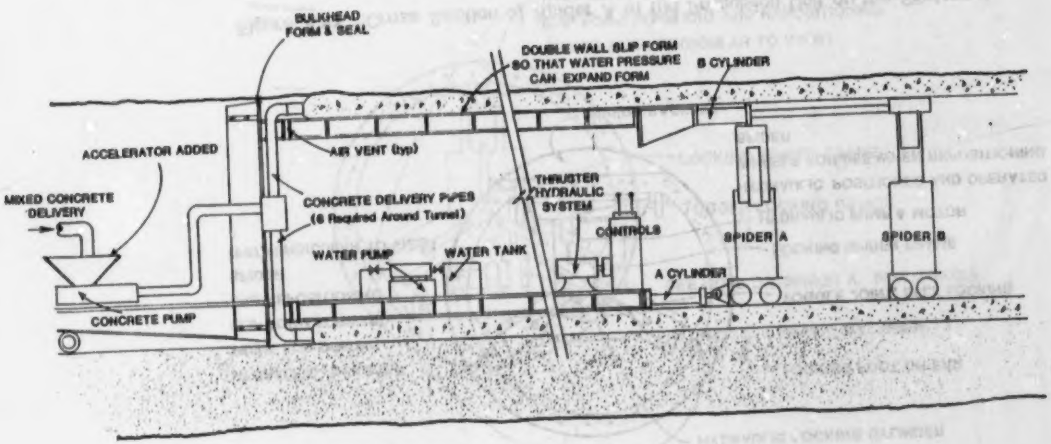
BULKHEAD FORM & SEAL
DOUBLE WALL SLIP FORM SO THAT WATER PRESSURE CAN EXPAND FORM
B CYLINDER
ACCELERATOR ADDED
AIR VENT (typ)
MIXED CONCRETE DELIVERY
CONCRETE DELIVERY PIPES (6 Required Around Tunnel)
THRUSTER HYDRAULIC SYSTEM
CONTROLS
SPIDER A
SPIDER B
WATER PUMP
WATER TANK
A CYLINDER
CONCRETE PUMP

Figure A10. Tunnel Slip Form With Self Propulsion Unit.

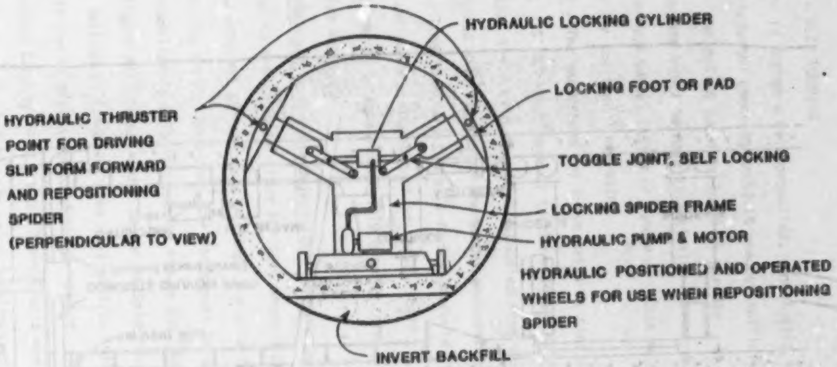
HYDRAULIC LOCKING CYLINDER
LOCKING FOOT OR PAD
HYDRAULIC THRUSTER POINT FOR DRIVING SLIP FORM FORWARD AND REPOSITIONING SPIDER (PERPENDICULAR TO VIEW)
TOGGLE JOINT, SELF LOCKING
LOCKING SPIDER FRAME
HYDRAULIC PUMP & MOTOR
HYDRAULIC POSITIONED AND OPERATED WHEELS FOR USE WHEN REPOSITIONING SPIDER
INVERT BACKFILL

Figure A11. Cross Section of Spider A of the Propulsion Unit on the Slipforms.

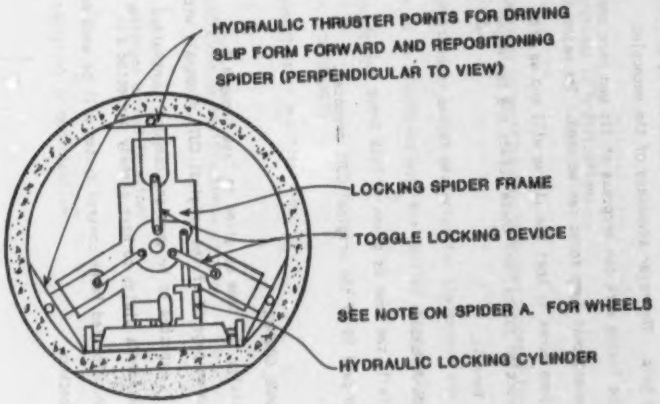
HYDRAULIC THRUSTER POINTS FOR DRIVING
SLIP FORM FORWARD AND REPOSITIONING
SPIDER (PERPENDICULAR TO VIEW)
LOCKING SPIDER FRAME
TOGGLE LOCKING DEVICE
SEE NOTE ON SPIDER A. FOR WHEELS
HYDRAULIC LOCKING CYLINDER

Figure A12. Cross Section of Spider B of the Propulsion Unit on the Slipforms

firm has offered help and design assistance. Another firm, Simons Company in New Braunfels, Texas, has also been contacted. It is believed this firm will also offer advice and help. The major advantage of the decoupled tunneling system is that the lining work can progress at its own pace and that if all else fails, conventional jump forms can be used. The major disadvantage of conventional jump forms is that the lining will end up with both cold joints and construction joints, and these joints are the major source of water leaks into tunnels.

TASK GROUP S5.5. - STRUCTURAL ANALYSIS

This section is essentially the same as given in Task Group 3.1. - Structural Analysis given on page 59 of the original CUTS proposal.

TASK GROUP S5.6. - DIRECTIONAL CONTROL

This section is essentially the same as given in Task Group 4.1. - Directional Control as given on page 68 of the original CUTS proposal, with the exception that the TBM is expected to be gyro and computer controlled. The Humphries Company in California claims to have already perfected a suitable gyro control system. The Zed laser control system will be used only as a secondary control and backup.

HEDULING OF TASKS

No additions or modifications.

ERSONNEL

No additions or modifications.

UDGET

. No additions or modifications to budget proposed for period 11/1/84 to 10/31/85.

. The preliminary budget projected for the second and third contract years is in accordance with the earlier discussion in this Addendum.

XHIBIT A - Delete

APPENDIX A - REFERENCES

No additions or modifications.

APPENDIX B

No additions or modifications.

APPENDIX C

No additions or modifications.

APPENDIX D

No additions or modifications.

APPENDIX A.A

SUMMARY OF REVIEW PANEL COMMENTS

The group seemed to be unanimous that at least two kinds of tunneling systems should be developed, one designed for soft ground such as CUTS and one designed for rock or competent ground. It was also tacitly understood by the group that the SSC project would likely be located in good ground where temporary supports would not be necessary. Concern was expressed that CUTS does not take full advantage of simplifications that should be possible in competent rock. There seemed to be agreement that in competent rock a tunneling system that is not unitized is preferable to one that is. The argument was that when any system component stopped, the whole system should be able to continue.

The panel seemed to believe our budget was inadequate for demonstration of the machine and perhaps for the construction of the machine.

Specifically, some aspects of CUTS were objectionable to some panel members but not all. These included:

1. A Con-Cor diagnostic probe ahead of the boring machine that would inhibit steering.
2. Slip forms to cast the tunnel lining which might get stuck in the tunnel.
3. Pneumatic transport of concrete materials and the mixing of concrete at the tunnel head where there is limited room.
4. Hydraulic transport of muck through a pipe in the floor of the lining which might be blocked, blown out, or eroded.

5. Water-jet assisted cutter bits which are not efficient.
6. Compressed air support of the freshly placed concrete tunnel lining that increases the labor costs and safety procedures.
7. Fiber-reinforced concrete which may ball up and block pipes, pumps, and mixers, as well as involve problems in handling the fibers.

Some panel members suggested that a revised tunneling system for competent rock be proposed for development. The suggestions included the following items:

1. Use only off-the-shelf equipment in the design.
2. Design using the "evolutionary" process instead of the "revolutionary" process of CUTS.
3. Separate operations for muck removal and concrete inflow should be through closely spaced, small-diameter service holes.
4. Mix all concrete at the surface and pump into the tunnel using a slick line.
5. Use ground radar to diagnose conditions ahead of tunneling operation.
6. Use jump forms if the tunnel must be lined.
7. Grout from the surface ahead of the tunneling operation in zones of bad or soft ground.
8. Do not try to get the maximum rate of advance.

In defense of the CUTS design, it might be added, some of the criticism by the panel contradicts the input from the previously contacted tunnel contractors and tunnel equipment and machine manufacturers, and even present-day tunnel literature. Much of the input before the last panel review agreed that:

1. The rate of advance controls tunnel costs.

2. The muck-removal system controls the rate of advance.
3. With conventional tunneling approaches, the interaction of the conflicting circulation systems and operations, such as track laying, erection of temporary supports, and switching of cars at the heading, severely limits the utilization of the tunneling system.
4. Tunneling needs a systems approach with a unitized machine to prevent circulation conflicts.
5. An automated machine is needed to decrease labor costs and insurance costs.
6. Advances in tunneling practice in the United States have seriously lagged behind Europe and Japan, largely because the industry is very conservative.

APPENDIX 13

NATIONAL RESEARCH COUNCIL □ NATIONAL ACADEMY OF SCIENCES □ NATIONAL ACADEMY OF ENGINEERING

Tunneling Technology newsletter

U.S. NATIONAL COMMITTEE ON TUNNELING TECHNOLOGY
2101 CONSTITUTION AVENUE, NORTHWEST □ WASHINGTON, D.C. 20418
TELEPHONE: [illegible]

SEPTEMBER 1985

NUMBER 51

The U.S. National Committee on Tunneling Technology has recently published the results of a three-year, case-history study of subsurface explorations for underground design and construction. The basic objective of the study was to discover improvements in practices and procedures that will enable planning and conducting more effective geotechnical site investigation programs.

The two volume report (1984) of the study is intended for a broad and disparate audience in terms of perspectives, needs, and goals. Therefore, Volume 1 begins with overview chapters and then becomes increasingly specific, proceeding through discussion of particular problems and projects, evaluation of selected cases, and interpretation of case histories. The final chapter reports the conclusions and recommendations. Volume 2, supplemented by separate data matrices, presents raw data in abstract form for the 87 projects reported as case histories and a computer program for managing the data to suit several purposes.

The article that follows is intended to acquaint the reader with the major findings of the study. Therefore, it concentrates on interpretation of the significant data collected and the conclusions and recommendations, both analytical and judgmental, developed throughout the course of the study.

GEOTECHNICAL SITE INVESTIGATIONS FOR UNDERGROUND PROJECTS

The high costs of underground construction are a major concern of both the general public and the agencies (federal, state, and local) that build or provide funds for a variety of projects. The U.S. National Committee on Tunneling Technology (1974; 1978) has issued recommendations addressing certain aspects of underground construction that contribute to its high risk and high costs. However, underground construction continues to be expensive, with project costs rising rapidly and often significantly exceeding the preconstruction estimate. Although there are a number of reasons for this, including periods of high inflation, one phase of the process of designing and constructing underground structures has become a promising target for scrutiny. That target is the exploration phase, specifically subsurface geology and site investigations. Essentially, geologic conditions constitute the greatest source of unknowns prior to actual construction of an underground project. These unknowns usually exist in inverse proportion to the amount, nature, and quality of the geotechnical investigations.

Of all large construction efforts, underground projects are particularly sensitive to geotechnical considerations because the construction environment both affects and responds to the design and construction processes as well as, ultimately, the operation of the completed facility. Therefore, an adequate and reliable determination of subsurface conditions is essential to every phase of the project and, as a consequence, may be a significant factor in the final cost.

Operating on this premise, a subcommittee of the U.S. National Committee on Tunneling Technology undertook an intensive study of subsurface exploration practices and procedures. The approach adopted was to examine various types of completed projects for which the results of the preconstruction site investigation could be related to the construction history. The study plan was designed to permit in-depth review of a large number of these projects, their respective site investigation programs, and the construction problems and unanticipated costs (or lack thereof), as a means of determining the nature and significance of the relationship between investigation programs and project problems and costs.

The subcommittee trusts the information and findings developed from the study will result in improvements in the planning of site investigations and in the securing of geotechnical data that are specifically needed by a variety of users. The ultimate result should be improvements in the economics, efficiency, and effectiveness of underground construction, thereby benefiting projects for which it is the only alternative as well as those where it may prove an advantageous alternative to surface construction.

INTERPRETATION OF CASE HISTORIES

Information concerning the 87 projects discussed herein was obtained through an extensive and complicated procedure that produced a large and complex body of qualitative and quantitative data for examination. Initial review of the comprehensive results was accomplished using two matrixes which displayed both original and calculated data. One matrix showed the 87 study projects plotted against an abbreviated "problems encountered" list (31 separate items grouped into 7 categories). The other matrix charted 57 different items of original and calculated data for each study project. The matrixes served as the basis for arithmetic tabulations, computer searches, sorting and selecting parameters, and plotting graphically. For correlation purposes, more than 70 plots were generated to sort data according to various combinations of parameters.

The results derived from the qualitative and quantitative information were reviewed for meaning and the more distinct of the pertinent results were selected for presentation. The discussion that follows is confined to matters that bear on the nature of the relationship between geology and construction and the significance of the geotechnical site investigation.

Results and Interpretation

The array of geotechnical conditions encountered in the 84 mined tunnels included in the 87 study projects is tabulated in Table 1. Overall, unstable ground is the most prevalent problem encountered during construction, with blocky/slabby and running ground cited most often as specific conditions (38 percent and 27 percent, respectively) for all the projects. Groundwater inflow is cited as a problem in 33 percent of the projects.

The percentage of incidence as a problem indicated for groundwater does not account for its role as a contributor to the incidence or severity of other conditions (e.g., flowing ground, face instability), which would raise its rating significantly. There may have been instances where unclear original sources of information led the subcommittee to label occurrences of "flowing" ground (which is wet) as "running" ground (which is dry). This is one of the reasons that the problem tabulations do not give as much weight to groundwater as it deserves. The subcommittee believes that water plays a large and varied role in tunnel construction difficulties; yet it may not always appear in the simplified listing of problems encountered in a project because it is a secondary contributor to the primary problem. For example, face instability would in many cases not have been a problem without the presence of water to reduce friction along joint surfaces or create seepage pressure, although the water might exist in quantities too small to deserve mention under groundwater inflow. In the same way, if only half of the recorded occurrences of running ground were really flowing ground, then that would raise by 12 the number of projects for which groundwater was a contributing cause of significant problems.

TABLE 1 Problems and Claims* Reported for Mined Tunnels

	Problems (% of tunnels)	Claims (% of tunnels)
Blocky/slabby rock, overbreak, cave-ins	38	16
Running ground	27	5
Flowing ground	5	4
Squeezing ground	19	0
Spalling, rock bursts	6	4
Groundwater inflow	33	6
Noxious fluids	6	4
Methane gas	7	1
Existing utilities	1	1
Soft bottom in rock	2	1
Soft zones in rock	4	2
Hard, abrasive rock (TBMs)	5	2
Face instability, rock	5	1
Roof slabbing	4	1
Pressure binding (equipment)	4	4
Mucking	5	1
Surface subsidence	9	2
Face instability, soil	11	5
Obstructions (boulders, piles, high rock in invert, cemented sand)	12	11
Steering problems	4	0
Air slaking	1	0

*The word "claim" is a shorthand expression that encompasses all requests for extras as a result of an unexpected subsurface situation.

Of all the problems, the highest incidence of claims (16 percent) was recorded for the grouping with the highest incidence of occurrence, i.e., blocky/slabby rock, overbreak, cave-ins. Of the other five conditions reported most frequently, three exhibit a similar relationship to claims. However, groundwater ranks several positions higher in problem incidence than in claim incidence; the ranking for obstructions is the reverse. Even so, the overall relationship is unchanged: the six conditions causing the most problems cause the most claims. Generally thereafter, it is difficult to determine a pattern by ranking.

However, the significance of a problem is related not only to frequency of occurrence but also to magnitude of impact. The tabulations in Table 1 can be translated to obtain a measure of impact by relating the incidence of claims to the occurrence of problems. This method reveals that the relationship between occurrence and impact can be inversely proportional, as shown by the ratings presented in Table 2. For comparison purposes, Table 2 lists the problem conditions according to their frequency of occurrence, from highest to lowest. The impact rating is on an ascending scale, with a maximum value of 10. (For quick comparison between problem occurrence and significance, the impact rating can [illegible]ultiplied by 10--i.e., a rating of 9.2 indicates a 92 percent incidence of claims per occurrence.)

Table 2 reflects considerable impact--a rating higher than 6.5--for six specific conditions, all of which occur infrequently: soft bottom in rock, pressure binding, obstructions, flowing ground, spalling and rock bursts, and noxious fluids. At this point the impact rating decreases suddenly, revealing six conditions closely grouped in the range from 5.0 to 4.0. In this grouping, the impact rating is moderately high and the frequency is generally low, but a trend begins toward more direct proportion (i.e., for blocky/slabby rock and squeezing ground). For the remaining problems, the impact rating then drops to 3.3 (running ground), clusters again with five conditions (including groundwater inflow) between 2.8 and 1.8., and then falls to 0.

TABLE 2 Impact Rating for Problem Conditions

Conditions (# problems or occurrence)	Impact Rating
Blocky/slabby rock, overbreak, cave-ins (38)	4.2
Groundwater inflow (33)	1.8
Running ground (27)	3.3
Squeezing ground (19)	4.3
Obstructions (12) (boulders, piles, high rock, cemented sand)	9.2
Face instability, soil (11)	4.5
Surface subsidence (9)	2.2
Methane gas (7)	2.8
Noxious fluids (6)	8.6
Spalling, rock bursts (6)	6.6
Hard, abrasive rock, TBMs (5)	4.0
Face instability, rock (5)	2.0
Flowing ground (5)	8.0
Mucking (5)	4.0
Pressure binding, equipment (4)	10.0
Roof slabbing (4)	2.5
Soft zones in rock (4)	5.0
Steering problems (4)	0
Soft bottom in rock (2)	10.0
Air slaking (1)	0
Existing utilities (1)	0

In certain instances (e.g., pressure binding), the severity of a problem can be linked with the sensitivity of the construction method to a particular condition. In others (e.g., overbreak, obstructions), it is less clear whether difficulty is more a function of the existing condition or the technique. It is likely that frequency of occurrence may sometimes be a moderating influence because it results in enhanced experience and ability to cope that offsets the problem to some degree. In part, this may explain why the incidence of claims and/or impact rating for some problem conditions (e.g., running ground) is lower in relation to prevalence than might otherwise be expected.

Unfortunately, several important aspects of the relationship between geotechnical conditions and construction problems cannot be readily discerned or computed. They are the length of delays and degree of inefficiencies that are introduced as a consequence, and their associated costs. The cost impact is not limited to construction dollars alone but extends to project reliability and longevity.

Although certain aspects remain ill defined, the plots and tabulations of numerical data yielded several interesting trends and quantitative values that help delineate the extent of the interaction of geology with construction and the effect of the geotechnical site investigation. The findings relate to the level of exploration, cost estimates, project costs, and claims.

Before discussion of the findings, the manner of reporting the data merits a brief explanation. For the tabulated data, results are generally presented as the arithmetic mean--referred to hereinafter as the "average," in the commonly understood sense of the word. For much of the plotted data, results are cited in terms of the "median." Here, the value expressed by the median is considered more accurate than the everyday form of averaging, because the median accounts for the effects of significant skew in the samples. The techniques for deriving the values differ and, therefore, the terms "average" and "median" are not used interchangeably.

Level of Exploration

In present practice, overall, the average number of boreholes drilled per 1,000 route ft* of alignment is 2.4--i.e., a spacing that approaches 415 ft. It should be noted that these figures are based on 84 projects, of which 20 percent are in mountainous areas where tunnel depth can often exceed 1,000 ft and hole-to-hole spacing can reach thousands of feet. When data for these tunnels are excluded in order to reflect more common practice, then the average number of boreholes per 1,000 route ft nears 3.9, for a spacing that is about 260 ft.

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*Route ft is a measurement of alignment that distinguishes between single and multiple tube configurations for the purpose of equating the utility of borehole surveys. For example, one borehole may be used to survey (theoretically) twice as many linear ft of tunnel for a double tube system as for a single tube system. Thus, one route ft in a double tube system comprises two linear ft of tunnel alignment; in a single tube system, route ft and linear ft are the same.

Although these tabulations provide a measure of exploration, they do not allow sufficiently for the effect of tunnel depth. Therefore, a more meaningful gauge can be obtained by determining the linear ft of borehole drilled per route ft of alignment. When the level of exploration is expressed in this manner, then the median lin ft of borehole per route ft is .34 in overall practice and .42 in common practice. (In this instance, the averages for lin ft per route ft are similar, .30 and .43, respectively.)

Exploration costs were extremely difficult to compile because separate records of the amounts spent were often not available or were incomplete. In addition, the task of apportioning costs for investigation programs overlapping several projects was complex. As a result, the figures for exploration costs are considered less reliable than others reported herein.

Of the 84 study projects, exploration costs for 36 were obtained. Information was sufficient for 30 projects (except as noted) to permit the extrapolations shown in Table 3. Although some inconsistencies in matching samples were encountered, the preponderance of the data was obtained from projects for which figures were consistently available for each item tabulated. Therefore, the small variation in matching samples was not a significant concern.

TABLE 3 Exploration Costs Compared to Construction Costs

	Construction ($ millions)	Exploration Costs ($ millions) Total	Expressed as % Construction Overall	Range	Median
Engineer's Estimate	$829.67*	9.20*	1.10	.02-24.4	.44
Basic Construction**	$661.28	11.53	1.74	.02-17.5	.75
As Completed	$694.88	11.53	1.66	.01-17.5	.70

*Figures are based on data for 28 projects.
**Costs excluding claims awarded.

Figure 1 illustrates more clearly the degree and nature of the scatter indicated by the range cited for exploration costs as a percent of construction costs. It is evident that funds expended for site investigation programs do not rise with increasing project costs. Rather, a significant number of the more costly projects (i.e., those in the upper half of the scale) exhibit a decrease in exploration funds to a point well below the median. It is in the mid range that the number of

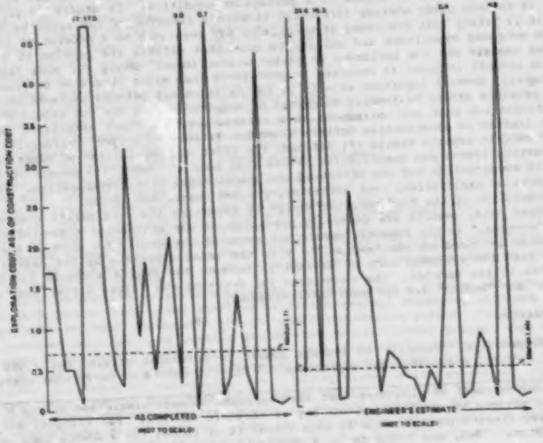

FIGURE 1

projects above the median generally equals the number below. However, only about 30 percent of these projects approach the median within a reasonably small range of scatter.

Overall, these results indicate that present practice is to devote a relatively small portion of project costs to a site investigation program. In some instances, low expenditures may be warranted because a sufficient body of information may be available from explorations conducted for overlapping projects, or nearby projects, or from other sources such as aerial surveys and regional geologic reports. However, these circumstances cannot be assumed to explain entirely the general low level of expenditures or the scatter in the data. Even though the cost of construction is not always in direct proportion to the geotechnical complexity or extent of a project, the relationship between these factors is obvious. On that basis, it is apparent that the level of exploration costs does not correlate satisfactorily with construction costs.

Estimates of Cost: Engineer and Contractor

The engineer's estimate is a measurement of costs that is used by the owner for a variety of purposes throughout the conceptual to completion phases of a project. Essentially it serves as a benchmark for the development and evaluation of the components of the planning, design, bidding, and construction processes. As such, the engineer's estimate is depended on to predict the actual project costs with reasonable accuracy.

Figures 2, 3, and 4 compare the as-completed costs for mined tunnels with the engineer's estimate. The comparison examines the cost relationship in terms of several parameters representing the level of exploration. The individual results combine to form a more comprehensive basis for correlation.

A review of Figures 2-4 reveals that as-completed costs differ significantly (±50 percent) from the engineer's estimate when the level of effort or funds devoted to geotechnical site investigations are low. This degree of variability is a reasonable occurrence only during the earlier stages of the initial conceptual work--i.e., when the exploration program is still in progress. This circumstance suggests that general exploration practice is providing inadequate information for reliably estimating as-completed costs. The suitability of the site investigation also must be considered for its sensitivity to the effort level, an important concern because of its potential influence on reliability.

The deviation between as-completed and estimated costs decreases as exploration increases. Figure 2 indicates that the engineer's estimate becomes a more reliable tool for predicting actual costs when sufficient exploration has in fact been accomplished--i.e., boreholes at greater than 0.6 linear ft per route ft. At this point, a substantial reduction is reflected in the frequency and degree of scatter above the estimate. A similar trend is exhibited in Figures 3 and 4, when funds expended exceed one percent. Decreasing scatter below the estimate is less marked in degree, but it is a tendency worth noting.

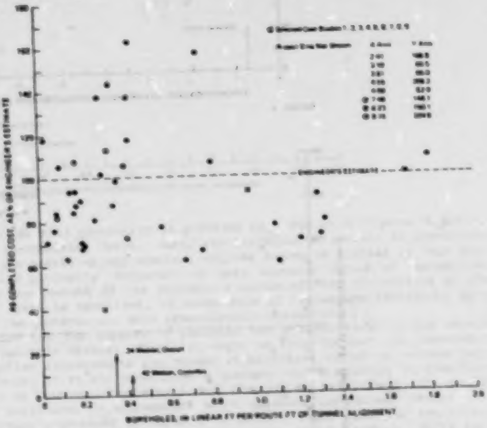

FIGURE 2

The contractor's bid was examined in terms of two of the three parameters used in evaluating the engineer's estimate. Appropriately, the major difference in approach was to review the relationship of the contractor's bid to both the engineer's estimate and as-completed costs. These results are presented in Figures 5, 6, and 7.

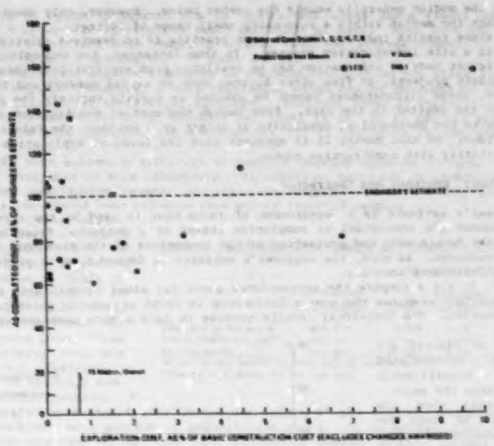

FIGURE 3

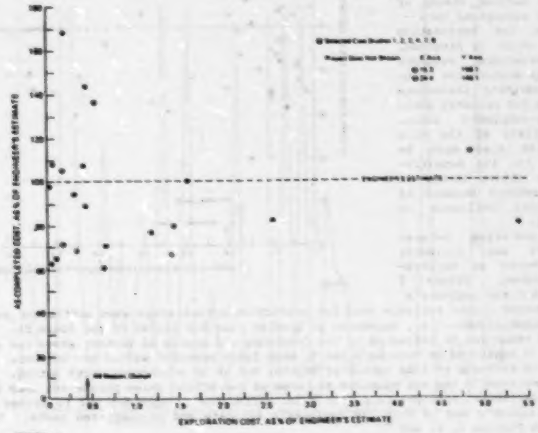

FIGURE 4

In Figure 5 it is apparent that the discrepancy (±50 percent) between the bid and engineer's estimate decreases as the exploration level nears and continues beyond 0.6 linear ft of borehole per route ft of tunnel alignment. Then, the bid begins to approach, and is generally less than, the engineer's estimate. Interestingly, it can be observed that Figure 5 reflects results distinctly similar to Figure 2 with respect to incidence, degree, and pattern of scatter.

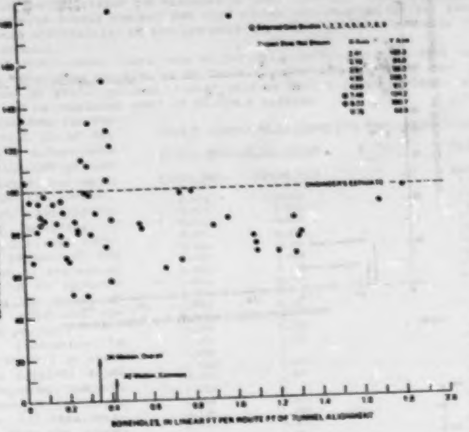

FIGURE 5

At least a partial explanation for this similarity is provided by a review of Figures 6 and 7, which compare the bid estimate and as-completed costs. Here, the incidence of scatter is consistent with that exhibited previously for low levels of exploration, but the degree of scatter is less pronounced (±30 percent rather than ±50 percent). Moreover, at more suitable levels of exploration (greater than 0.6 for boreholes or one percent of the engineer's estimate), the convergence of the contractor's bid with as-completed costs is excellent, in terms both of degree and consistent pattern. The benefits resulting from the geotechnical site investigation are obvious.

The difference in effects noted for the engineer's estimate and the contractor's bid merits attention to consider some of the possible causes. First, it might be expected that the contractor would be more experienced in evaluating requirements for tunnel construction suited to various purposes and ground conditions. Moreover, it is the contractor's business to be accurate in determining the cost of individual elements so that an advantageous cash flow can be maintained. The margin between profit and loss is rarely sufficient to accommodate major inaccuracies without severe consequences. In comparison, the engineer's estimate is intended to predict total costs for the entire project (of which the mined tunnel is only a part) with a reasonable degree of accuracy, which permits a more flexible approach. However, this built-in tolerance can be diminished or even eliminated if the estimating process is constrained. Among the elements that particularly influence the results are inflation before and during construction, constructibility, and detailed subsurface information. If policy, procedures, or circumstances limit the determination or incorporation of any such basic components, then the accuracy of the engineer's estimate can be reduced accordingly and often to a profound degree. As inaccuracies escalate, it is increasingly difficult to avoid distortion of the estimate for the entire project.

Certainly the bases for accuracy differ somewhat between contractor and owner, as well as the strictness of the criteria. In the final analysis, only the owner can determine if the criteria have been satisfied when the engineer's estimate is simply higher than as-completed costs.

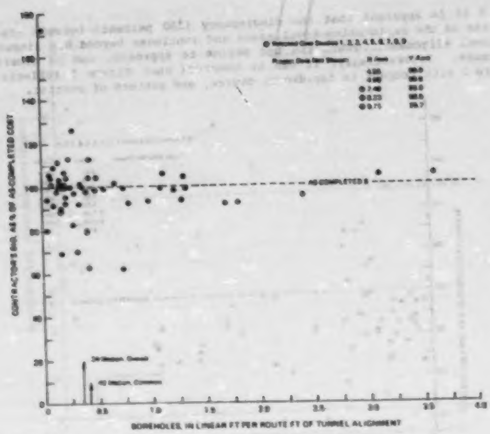

FIGURE 6

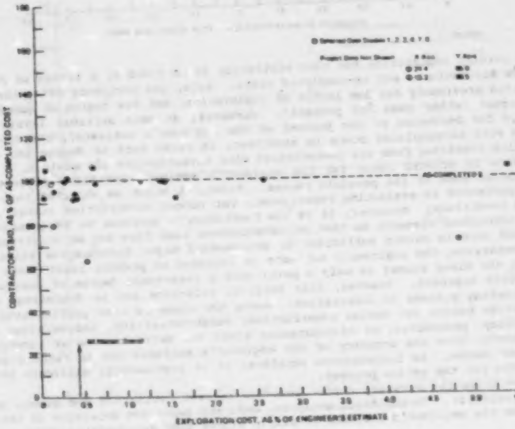

FIGURE 7

Claims

Requests for extra payments for unexpected subsurface situations--i.e., claims--appear to be a significant part of tunnel cost. Of the 84 mined tunnels studied, 49 reported claims related to geologic and/or subsurface conditions. (Three of these claims were for comparatively small amounts, i.e., less than $25,000.) Projects without claims totaled 29, and there were 6 for which no information was available on whether claims had occurred or not. Overall, then, it appears that about 60 percent* of tunnel projects entail claims, and that claims are substantial for about 55 percent of the tunnel projects. Stated differently, of the projects experiencing claims, nearly 95 percent of the claims are for large amounts.

Of the 49 tunnels with claims, there were 32 for which sufficient data were reported (Table 4) to permit evaluation. Combining the figures in Table 4 yields the following sums (in constant 1982 dollars): total claims of $253.7 million, claims paid of $161.8 million, basic construction costs of $1,364.8 million, and as-completed costs of $1,526.6 million.

Examination of the data for the 32 tunnels reveals that 11 of the claims (8 major and 3 minor) were settled for essentially 100 percent of the amounts requested, one major claim was settled for 115 percent, and 3 major claims were settled for zero payment. The remaining 17 claims were settled for sums varying from 10 to 70 percent of the amount requested, for an average of 39 percent. There is no apparent relationship between the amount of the claim--made or paid--and the original size of the project.

Overall, the indication is that payments were settled at about 64 percent of the original total claimed. These payments amounted to nearly 12 percent of the basic construction costs. (If this average were computed from the claimant's viewpoint--i.e., increase the as-completed total by $91.9 million [the difference between claims made and paid] to reflect construction costs considered justifiable--the settled payment would approach 18 percent.)

TABLE 4 Comparison of Claims with Construction Costs

Totals* Reported for Claims		Totals* for Construction	
Claims Made	Claims Paid	Basic**	As-Completed
0.008	0.008	4.69	4.7
0.008	0.008	12.59	12.6
0.010	0.010	4.79	4.8
0.080	0.020	10.18	10.2
0.250	0.150	11.65	11.8
0.350	0.350	16.15	16.5
0.600	0.600	14.4	15.0
0.680	0.170	16.43	16.6
0.700	0.700	21.4	22.1
0.747+	0.747+	32.3	33.05
0.787	0.387	25.013	25.4
0.800	0	5.9	5.9
1.000	0.200	15.2	15.4
1.290	0.270	28.63	29.2
1.400	0	19.4	19.4
1.600+	1.600	29.8	30.6
1.800+	1.800	99.9	101.7
2.000	0	275.5	275.5
2.100	2.100	51.2	53.3
2.100	1.200	72.6	72.7
2.600	1.300	32.3	33.0
5.400	3.000	18.5	20.5
6.900	1.300	29.7	31.0
7.500	0.750	19.55	20.3
8.100	2.900	73.22	76.2
11.800	3.400	42.6	46.0
19.200	11.100	104.5	115.6
25.100	7.950	140.55	148.5
25.100+	25.100	44.2	69.3
28.200	20.200	34.0	55.0
37.000	7.500	29.0	37.3
58.500	67.400	29.1	96.7

*Constant 1982 dollars, in millions.
**Costs excluding claims paid.

In view of these results, the possible influence of the exploration program is an unquestionably relevant concern. Therefore, claims were reviewed in terms of several parameters that served for correlation in the preceding sections. To obtain an appropriate comparison, the data base was expanded by removing the limitations imposed for Table 4. Claims made were examined in terms of both the engineer's estimate and contractor's bid, and then compared with the exploration level for boreholes.

Results of the comparison, presented in Figure 8, indicate a well defined relationship between claims and the exploration effort. At low levels of exploration, approximately 50 percent of the requests were for amounts greater than 10 percent of the engineer's and contractor's estimates. Overall, claims averaged 29 percent of the engineer's estimate and almost 28 percent of the contractor's

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*It is possible that this figure may be low as an extrapolation to industry-wide occurrence. At least two owners who volunteered completed projects are known to have each withheld one newly completed project with claims currently in litigation. If very many of the participating owners faced similar dilemmas, then the sample may be biased toward the "no claims" end of the study spectrum. Also, some projects with litigation completed may have been withheld to avoid possible embarrassment to any interested parties. The subcommittee hopes that the potential for distortion is minimal and limited to unresolved claims.

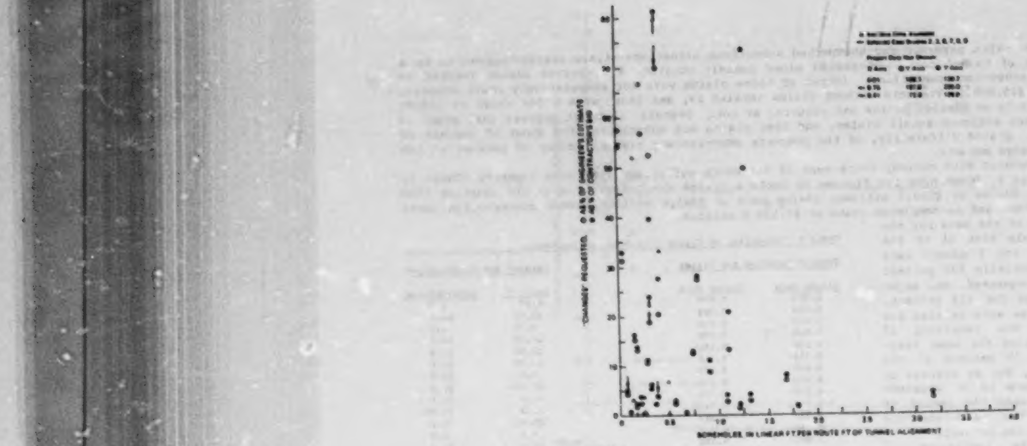

FIGURE 5

bid. As soon as exploration exceeds 0.6 linear ft of borehole per route ft of alignment, a marked decrease occurs in the number and size of the claims. This trend downward continues sharply as the borehole level exploration increases. A similar comparison of claims and funds expended for exploration produced matching results. Thus, it is clear that the site investigation program can moderate the occurrence of claims and their severity.

Project Costs

The ultimate cost of projects can be estimated accurately and controlled or moderated without sacrificing fair compensation. These goals are attainable when the site investigation program is conducted at a sufficient level to permit thorough evaluation of the subsurface by all parties to the construction process and according to their specific needs. However, the exploration program can only contribute successfully to these goals if the level of effort is increased as a matter of general practice. This belief is based in part on the following findings, which relate to the relationship between exploration and project problems and costs.

- Of all the projects studied, only 11 reported no significant problems and none reported minor problems alone. For more than 85 percent of construction projects, the typical level of site investigation is too low to characterize subsurface conditions adequately in order to plan for or avoid impact on constructability. This circumstance leads to inaccurate budgets and schedules, inappropriate construction procedures, unnecessarily (often) high increases in as-completed costs, claims and litigation, and difficulties with operations and maintenance.
- The engineer's estimate varies ±50 percent from both bid costs and as-completed costs at the levels of exploration commonly practiced. These deviations are a source of uncertainty for the owner, contractor, and the public, and promote costly adversary relationships. When typical exploration practice is increased, bids and as-completed costs tend to equal or even fall below the engineer's estimate.
- Claims related to unanticipated subsurface conditions occur for about 60 percent of construction projects. In some instances, a claim may be part of the fair cost of a project. Overall, however, claims and disputes result in inefficiencies that are expensive for the owner and contractor. Improving site characterization by increasing exploration reduces the incidence of claims and attendant effects; when unnecessary claims are avoided, construction is more economical.

- A significant portion of project costs stems from claims settlements rather than from investigation of the site for design and construction purposes. The typical one percent (about) of project costs expended for exploration is obviously too low when compared with the average 12 percent of project costs devoted to settled payments for claims. If this figure were extrapolated from 65 to 100 percent of the projects reporting claims, then the average minimum settlement is slightly greater than 7 percent of project costs. However, these averages represent only the amounts publicly paid in settlement of a claim. For the adversaries, there are additional costs for staff and legal services that usually are not disclosed. These "hidden" costs can be tremendously high, and in some instances may reach a total that represents a significant portion of the project cost.

The geotechnical site investigation cannot predict every problem that may be encountered, and attempts to do so generally result in programs that are disproportionately expensive for the value received. For every underground project, cost-benefit is a key element. Increasing the level of effort and funds for exploration is demonstrably beneficial and cost-effective.

SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

The subcommittee's judgments on matters that bear on achieving the study objective are reflected in the conclusions and recommendations. Some of the judgments were strictly derived from data contained in the case histories. Others were influenced by subcommittee experience and knowledge of projects that could not be documented in detail, but collectively represent many more than 87 projects over a 20-year time span. Even though the basis for development differed, all of the findings are equally valid in the view of the subcommittee.

Conclusions

The conclusions, summarized here, generally offer a view of current industry practice and areas that could be improved. In a few cases, the conclusions are simply observations of fact and required no particular analysis or deliberation. In others, suggestions for changes in current practice are implicit in the way the conclusion is stated.

> **It is in the owner's best interests to conduct an effective and thorough site investigation and then to make a complete disclosure of it to bidders.**

Uncertainty as to risk promotes increased costs and fosters disputes and litigation. A variety of legal precedents would make the owner responsible if actual site conditions are found to differ materially from those indicated by preconstruction subsurface explorations.

> **Disclaimers in contract documents are generally ineffective as a matter of law, as well as being inequitable and inexcusable in most circumstances.**

Disclaimers of information supplied are an inadequate means of managing risk; their use introduces ambiguity. Provision of differing site condition and changed condition clauses allows appropriate allocation of the risk of subsurface uncertainties.

> **Contracting documents and procedures can provide for resolution of uncertain or unknowable geological processes or conditions before and during construction, rather than afterwards.**

Clauses covering differing or changed conditions do not necessarily provide a mechanism for prompt resolution of the issue. Adopting a baseline of risks (or geotechnical data) before construction would permit timely recognition of a contract change and cost adjustment during construction, if conditions vary materially.

> **On major projects especially, it is important that (a) the owner employ a multidisciplined team including engineering geologists, engineers, and a construction specialist to develop subsurface data and evaluate their impact on design and construction; (b) designers and geologists possess a thorough working knowledge of construction methods and equipment so that the proper geotechnical data are secured and design is consistent with construction systems; and (c) contractors employ geologists experienced in underground work to evaluate and interpret the data provided at the time of bidding, thus ensuring that all the information obtained is fully considered in preparing bids.**

The most extensive and effective geologic site investigations are of limited value if not incorporated fully into the design, estimating, and bidding processes. Too often the significance of geologic site conditions is not emphasized appropriately. Current and developing underground construction methods demand greater attention to the collection and application of geological information.

Site investigations have to proceed through, but should not always end with, completion of the feasibility/alignment setting/final design programs.

The preconstruction site investigation should be an iterative process; appropriate data must be collected and analyzed to support the requirements of all project phases. Anomalies should not be left unresolved by the presumed "final" program.

Procedures for logging, documenting, and preserving samples from boreholes require improvement.

The quality and reliability of information obtained from boreholes are reduced when procedures are inadequate. Boreholes should be observed and logged by experienced engineering geologists. To document conditions, color photos should be taken as soon as possible after removal of the cores from the borehole. Special preservation techniques should be used for cores that deteriorate rapidly.

Geophysical methods can be used to advantage, especially in coordination with boreholes.

Many geophysical techniques are not widely used or applied to construction projects, yet have the potential to greatly expand knowledge of the subsurface when used to interpolate between boreholes. For example, these techniques can be used to identify anomalies where borings should be made.

Groundwater and its effects on the subsurface materials merit greater attention in exploration programs.

The presence of water accounts, either directly or indirectly, for the majority of construction problems. Most major tunnel projects should have one or more long-term pump tests to evaluate the various formations and conditions expected. Chemical tests of groundwater should be performed routinely.

Laboratory testing of the subsurface materials generally needs to be increased.

In rock tunnels, for example, at least 50 to 60 unconfined compression tests for each significant lithologic unit are needed to adequately characterize strength values. Silica content is an important parameter in predicting advance rates and abrasive wear.

Exploratory adits and shafts are generally justified only when absolutely essential to obtain critical design data or when a substantial benefit to construction is indicated.

These exploratory techniques are of questionable cost-benefit in many cases. Generally, the money expended on such techniques may be used more effectively for additional boreholes, groundwater investigations, laboratory testing, or engineering evaluations. However, there are alternative views.

Maintenance of technical data obtained during design and construction of underground projects often is not pursued by owners or demanded of their consultants and contractors.

A surprising quantity of exploration, design, and construction data is poorly recorded, filed without easy access, lost, or discarded by owners, construction contractors, and others. Yet, relatively few major underground projects fail to develop problems during their operational lifetimes. In many cases, data obtained in the various phases of the project are essential to defining the cause of the problem and the best method of correction.

Recommendations

These summary recommendations offer the more specific statements on how the tunneling industry can generally upgrade subsurface investigations and expand their uses. Most of the recommendations are firm proposals for policies that can be implemented within a short period of time. The others concern areas where research and development benefit predictions and explorations techniques.

Expenditures for geotechnical site exploration should be increased to an average of 3.0 percent of estimated project cost, for better overall results.

The low level of expenditure typical of current practice does not correlate well with estimated and actual costs or with construction problems and claims. For example, the amount of project costs devoted to exploration averages one percent and the amount devoted to claims payment averages 12 percent.

The level of exploratory borings should be increased to an average of 1.5 linear ft of borehole per route ft of tunnel alignment, for better overall results.

Current boring practice is not consistent with the evidence that boreholes are the best single exploration technique for providing reliable information to designers and contractors. Deviations between the final tunnel cost and both the bid price and engineer's estimate begin to decrease at 0.6 lin ft of borehole, with more desirable results achieved as the level continues toward 1.5 lin ft.

The owner should make all his geotechnical information available to bidders, while at the same time eliminating disclaimers regarding the accuracy of the data or the interpretations.

Some owners withhold from bidders as much of their interpretive information as possible in order not to be held responsible for any mistakes made in extrapolation from hard data. When this occurs, contractors bid according to various levels of personal experience and access to other sources of information. Bidding contingencies tend to be high to cover the construction unknowns.

All geologic reports should be incorporated as part of the contract documents.

Some owners make all of their subsurface data available to bidders, but do not making it a binding contract document. In such cases, the data are often accompanied by a disclaimer. Therefore, bidders may be reluctant to rely on the information for construction purposes in spite of its possible accuracy. One likely consequence is inconsistent and inaccurate bids.

Designers of mined tunnels should compile a "Geotechnical Design Report," which should be bound into the specifications and be available for use by bidders, the eventual contractor, and the resident engineer.

Bidders can easily remain uninformed on important design/construction matters that may have been seriously considered prior to the letting of bids, because the geologic report cannot comment on many of the late-developing plans worked out by the designer. The goal of the "Geotechnical Design Report" should be to explain the geotechnical rationale for design and the anticipated effect of geology on construction. The results can be expected to include improved construction procedures and probably a reduction in bidding contingencies.

Monitoring of ambient conditions prior to construction should be undertaken to establish a baseline of information for comparison during and after construction.

Records of specific data can be useful in preventing or settling disputes related to construction conditions or effects, as well as in protecting both owner and contractor from frivolous claims.

Pre-bid conferences and site tours should be conducted to ensure that all bidders have access to the maximum amount of project information.

Such conferences and tours supplement the utility of the geotechnical subsurface investigation. For example, pre-bid conferences are an effective means of assuring that all potential bidders have an opportunity to clarify any confusing issues in the contract documents. Site tours allow bidders to get the "lay of the land" and see the physical features of the project for themselves. This is especially important in cases where a test adit or shaft has been constructed.

Geologic information from preconstruction explorations and as-built tunnel mapping and construction procedures should be compiled in a report detailing project completion.

Without such a report, there is no formal way for an owner to confirm geologic predictions and find out where assumptions were right or wrong. There is also no easy way to resurrect records of operations and apply the experience to future projects in order to avoid the repetition of errors. Information on actual construction (or geologic) conditions can be invaluable in the event of damage to or malfunction of the tunnel during its operational life.

Investigation methods and predictions should be improved for three specific conditions: in-situ stress, stand-up time, and groundwater.

In-situ stress is one of the conditions not always adequately predicted by designers. Instruments and predictive techniques need further development, especially for stresses at great depth and particularly when coupled with below average rock strength. Stand-up time is important for design and bidding, and is a major consideration in selecting appropriate construction methods. Yet, estimates of stand-up time developed from information prior to construction are usually indefinite (or not provided). Groundwater--occurrence, behavior, and effects--accounts either directly or indirectly for the majority of problems encountered in underground construction. Developing better quality field pump tests, increasing understanding of the effects of even a small amount of water flow, and establishing a data base would assist in sorting and evaluating the complexities of the problems presented by groundwater.

> Improved horizontal drilling techniques should be developed that can recover rock core and penetrate long distances without wandering from line and grade.

The need is especially severe for tunnels beneath mountains where, except for portal areas, difficult access and/or great depth generally make vertical boreholes difficult to drill accurately. Moreover, drilling the number of boreholes necessary for adequate investigation becomes prohibitively expensive.

> Research and development should be conducted to expand the capabilities of geophysical or other remote sensing methods for obtaining geotechnical data between boreholes and from the surface down to depths too great for boreholes.

A higher degree of interpretation/extrapolation is required to glean information from depths too great for economical borehole penetration. The process can be greatly assisted by techniques of geophysics and remote sensing, which can cover continuous extents of ground. However, relative lack of preciseness is a concern. Development of these techniques to the point that their results were as reliable as borings (and trusted equally by both designers and contractors) would enhance subsurface investigations.

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APPENDIX 14

SSC-15

Superconducting Super Collider

Siting Parameters Document

A Technical Advisory on
SSC Site Criteria and
Catalog of Site Information Needs

June 15, 1985

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SUMMARY

The Superconducting Super Collider, or SSC, is a proposed scientific instrument for the study of the fundamental nature of matter. In the SSC two 20-TeV beams of protons will be accelerated and counter circulate on an approximately circular path. The protons will be made to collide at six locations where detectors can be placed to count and measure the products of the collisions. These collisions, twenty times more energetic than in any existing facility, will enable scientists to probe deeper into the heart of matter in the quest for a deeper understanding of the universal forces of nature.

The goal of the SSC project is to create a scientific laboratory in high energy physics whose facilities are unique. Ultimately the success of that laboratory will be measured by its scientific discoveries, measurements, interpretations, and innovations. Toward that end the accelerator-collider must be constructed to high standards at minimum cost and maximum effectiveness. Preparations must be made for future operations and a scientific-technical staff attracted and maintained. The chosen site must accommodate all of these factors.

This document summarizes siting criteria for the SSC and enumerates site-specific information important to the evaluation of potential sites. This document is not a call for site proposals but a technical report prepared for the information and use of the Department of Energy (DOE).

The Reference Designs Study (RDS), published in May 1984, examined three technological approaches to a proposed 20-TeV proton collider. The site criteria presented here are derived largely from the RDS. Final details of the facility layout and building structures required will depend upon the actual site. The RDS is a model of such a facility that meets the scientific criteria and provides adequate working space for the activities and personnel associated with the SSC. The central feature of the facility will be a tunnel buried at least 20 feet below the local ground surface. The minimum circumference of this more or less circular tunnel is determined by the strength of the magnetic field that guides the beam along its path. Two field strengths, 3 and 6 tesla, are now under consideration and a choice will be made and announced by the end of September 1985. These correspond respectively to circumferences of about 100 and 60 miles.

An injector complex serves as the source of the protons to be accelerated in the collider ring. Its major feature will be a ring tunnel approximately five percent of the circumference of the collider ring. The location of the injector complex on the perimeter of the collider ring can be arranged to suit a site.

The loci of principal experimental physics work will be collision halls housing the detectors at the interaction points, together with adjoining areas where beams derived from the collider ring beams may be used for tests/experiments. These six halls may be distributed evenly around the ring in a periodic manner or they may be clustered in two or three groups. A study of the feasibility of clustering will be complete by the end of September 1985.

While the total space required for laboratories, shops, offices, warehouses, and auxiliary equipment will be approximately as described in the RDS, their form and placement has considerable flexibility for adaptation to a particular site. The bulk of the area within the collider ring will be totally unaffected by the presence of the facility, although control of and access to the associated surface buildings will be required.

The relevant site criteria and desired information fall into the following broad categories:

Physical Setting. A site must accommodate the accelerator, conceived of as a planar ring 60 to 100 miles in circumference with the possibility of a slight tilt to accommodate the profile of the land, and must have available up to 11,000 acres of land appropriately distributed around the ring.

Environmental Aspects. A site should be such that the SSC facility can be positioned, constructed, and operated in an environmentally acceptable way.

Geology and Tunneling. The geology of a site must be such as to allow efficient tunneling with resulting structural stability and without encountering excess water.

Community Resources. A site should provide year-round access by road, have a major airport nearby, have adequate housing and educational facilities potentially available for the staff, and adequate industrial and construction resources in the vicinity.

Utilities. A site should have available adequate and reliable water (up to 2000 gal/min) and electrical power (up to 250 MW).

Man-Made Disturbances. Accelerator operation requires avoidance of excessive very low frequency noise and vibration adjacent to the tunnels.

Climate. Ease of construction, and cost and reliability of operation of the facility make desirable the avoidance of extremes of temperature and humidity.

Cost and Schedule Factors. Economies in construction and operation as well as proposed cost sharing for land, preferential utility rates, and similar items are important considerations.

Part III of this report gives more precise and detailed statements of the site criteria including numerical values where appropriate. Part IV itemizes the detailed information desired in order to make an informed evaluation of any site.

Approximately 3000 scientists, engineers, and technicians will operate the facility and carry out its scientific work. The environmental impact of the facility will be similar to that of a campus of a university or a corporate research center. It is estimated that the capital cost of the facility itself, together with the initial complement of scientific equipment, pre-operating costs, and R & D, will be about $4 billion (in FY-1984 dollars). A construction time of about six years between notice to proceed and completion is anticipated.

The principal objective of this advisory is to delineate for the Department of Energy those technical factors affecting the choice of a site for the SSC. The goal is the creation of a laboratory that will ensure the capability and effectiveness of the U.S. research program in elementary particle physics well into the next century.

More information of the research potential of the SSC is contained in a booklet, "To the Heart of Matter -- The Superconducting Super Collider," and the articles and books cited in its bibliography. Copies of this informational booklet are available from the SSC Central Design Group.

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PART I. SSC PROJECT DESCRIPTION

A. INTRODUCTION

The proposed Superconducting Super Collider (SSC) will be one of the largest scientific instruments ever made; its major feature is a giant ring— up to 100 miles in circumference— in which the basic constituents of matter are created and studied at an energy of 40 trillion electron volts, twenty times greater than at any existing facility. Particle physicists here and abroad agree that the construction of the SSC within a decade will give scientists timely access to an instrument unrivaled in the world for making frontier discoveries well into the next century.

To the passerby or guest who visits the SSC some time after its completion in the mid-1990s, the focal point of the site will present the appearance of a university or research center campus, with a central multistory office building, numerous laboratories, shop buildings, and other support buildings. The heart of the facility, a ring-shaped or oval tunnel 60 to 100 miles in circumference and about nine feet in inside diameter, is buried many feet under the ground, while the landscape above it gives few clues to what lies beneath. Where the ring passes below farm land, crops grow and cattle graze; where it traverses forests and remote areas, the land yields no signs of construction; where it passes under highways, towns, and rivers, life goes on as usual. Every two to four miles, small surface buildings— containing power supplies, support facilities, and points of access— connect to the tunnel, and at several locations around the ring larger complexes of buildings signal the location of interaction regions containing detectors for experiments. Figure 1-1 is a possible bird's eye view of a site. Some 3000 men and women will be working on any particular day at the SSC facility— scientists and engineers and technical and administrative staff— including 500 visitors taking part in research projects.

The SSC is a particle accelerator, one of a family of scientific instruments that has been in the forefront of scientific discovery in the twentieth century. The development of particle accelerators, coupled with the discovery of natural radioactivity earlier in the century, led directly to the establishment of the field of science known as high energy physics, a field in which American scientists have made major contributions.

High energy physics, often called particle physics, is the study of the ultimate constituents of matter. The particle accelerator is its chief tool because with the collisions of very energetic particles, scientists can observe in a direct way the basic building blocks of nature and the forces that hold them together. The progression from the first cyclotron, 5 inches in diameter, to the proposed SSC, 20 to 30 miles in diameter, is a direct consequence of the need to probe at ever smaller distances, deep into the heart of matter.

Accelerators work by using a series of electromagnetic kicks to boost charged particles like protons (the nuclei of hydrogen atoms), or electrons to ever-higher energies. When they reach their maximum energy the particles are directed against a target that contains either the same or other types of particles. The collisions cause the release of substantial bursts of energy, out of which new forms of matter emerge. The resulting particles are detected and studied in large-scale electronic detectors that measure such basic characteristics as energy, electric charge, mass, and lifetime. In this manner, particle physicists illuminate the interconnections that exist among the fundamental laws of nature and gain insight into the generation of matter.

Accelerators can be configured in straight lines, in which case the particles are accelerated by passing once through a series of electric fields. The largest such linear accelerator, or linac, is the two-mile-long machine at the Stanford Linear Accelerator Center (SLAC) in California.

Most present-day high-energy accelerators, however, are circular. In the cyclotron, invented by the American physicist Ernest Lawrence, particles circle in a magnetic field and on repeated revolutions pass through a constant-frequency alternating electric field that adds small amounts of energy on each pass. This causes the particles gradually to spiral outward to a maximum radius while gaining energy. In the cyclotron, the time for a particle to make one orbit is constant.

The design of the cyclotron was improved upon in the forties and fifties by the invention of the synchrocyclotron and the synchrotron, which allowed physicists to generate beams of particles at much higher energies. In such machines, the frequency of acceleration is synchronized with the particle as it makes successive orbits, the time for each particle to orbit the machine varying with change in particle energy. The synchrocyclotron has an unchanging magnetic field, but an accelerating electric field whose frequency is decreased gradually as the outwardly spiraling particles take longer and longer to make successive revolutions as they gain energy. The synchrotron, on the other hand, maintains a fixed orbit radius for the particles, varying both the magnetic field and the frequency of the accelerating electric field in time as the particles gain energy. An important virtue of the synchrotron is that the guiding field around a large circumference is provided over only a small volume within a ring of magnets. This approach leads to economy in construction as well as in operating costs.

Each decade since the 1930s has seen more than a tenfold increase in the energy of the particles produced by accelerators: from cyclotrons with a few million electron volts (MeV) of energy in the mid-thirties to today's huge Tevatron at Fermilab, the U.S. national accelerator laboratory in Illinois, with its beam of 1 TeV (one trillion electron volts).

An important development in the progression was the discovery of the principle of strong focusing in the early 1950s. Strong focusing systems in particle accelerators consist of a series of magnets, one strongly focusing the particles horizontally but defocusing them vertically, followed by another that does the opposite. It was discovered that this sequence of alternating magnets has the remarkable property of strongly focusing and constraining the transverse size of the particle beams. As a result, beam pipes could be made much smaller, as could the magnets that surround them. The cost per unit length of synchrotrons was significantly reduced, thus making larger machines economical. A later, simplifying development for the larger machines was the introduction of "separate function magnets," dipole magnets to provide the necessary bending of the orbits, and quadrupole magnets to accomplish the strong focusing.

To understand the interplay of particle energy, magnetic field strength, and circumference of an accelerator, it is useful to take note of the following relation. The bending radius, R, in kilometers is related to the energy, E, in TeV (technically, the momentum times the speed of light) and the magnetic field, B, in teslas according to

$$R\ (\text{km}) = \frac{10\ E\ (\text{TeV})}{3\ B\ (\text{tesla})}$$

The higher the magnetic field, the smaller the bending radius for a given energy. For a circular ring, the minimum circumference is $C = 2\pi R$. In practice, the separation of functions of bending and focusing, and the presence of straight sections without magnets causes the circumference to be 25 to 50% larger than the minimum value. One example, to be discussed later, has B = 6 tesla, E = 20 TeV, leading to a bending radius, R, of 11 km. However, the design circumference is 96 km (60 miles), roughly 40% larger than the calculated ($2\pi R$) circumference of 69 km.

During the the late sixties and the seventies, the most significant advance in accelerator technology was the development of techniques leading to head-on collisions between two beams of particles—in contrast to the older method of aiming a single accelerated beam at a stationary target. In collisions with a stationary target, much of the energy of the incident particle is expended in causing itself and its collision partner to move forward at high speed. Relatively little energy is left for interesting effects such as new particle production. Head-on collisions permit utilization of all of the energy of the two beams for research purposes. For example, it would take a fixed target machine with a beam energy of 2000 TeV (with a circumference of 8000 miles!) to equal the useful energy available in a head-on collision between two protons that have been accelerated to 1 TeV (in a circumference of 4 miles). Because of such advances in accelerator technology, the energy range that is accessible to scientists has increased more than a millionfold in the past 50 years, while the cost per electron volt of beam energy has decreased dramatically during the same period.

Machines in which head-on collisions occur are known as "colliders." A collider is usually designed as a "storage ring," in which particles can be collected, accelerated, and stored. If the colliding particles are protons, they can be stored for as long as several days while repeated collisions take place. The colliders and storage rings that have been built so far have all been configured as circles or ovals. They range in size from a few feet in circumference to 4 miles for the largest now in existence, the collider at CERN in Geneva, Switzerland with 0.3-TeV beams and the soon-to-be-operational Tevatron collider at

Fermilab, with its 1-TeV beams.

The significance of the Tevatron is greater than might be inferred merely from the fact that as a collider it will soon provide collisions with three times the energy of the CERN machine. Operating since late 1983 in a fixed target mode, the Tevatron is the world's first large accelerator to exploit superconducting magnet technology. The addition of roughly 1000 superconducting dipoles and quadrupoles in the existing tunnel has permitted a two-fold increase of the energy of the machine with no increase in size. Superconducting magnets are doubly advantageous, providing greater maximum magnetic field strengths coupled with small electrical power requirements. The feasibility of the SSC depends in part on these proven qualities. It will be the largest collider and storage ring in the world, with an energy of up to 20 TeV in each beam particle, or a total useful collision energy of 40 TeV.

While the discussion so far has stressed the final energy of the beams and the accompanying ring of magnets of very large circumference, there is an elaborate sequence of operations before the accelerated particles enter the final ring. It is technically very difficult at high energies to increase the energy of a proton by more than a factor of ten or twenty in any given configuration of magnets. The reason can be seen in the relation stated above among the magnetic field, B, the energy, E, and the bending radius, R. For a fixed radius, as in a synchrotron, the energy and field are kept in proportion. Protons injected at a low energy must start in a low field. As the radiofrequency electric fields cause them to gain energy, the magnetic field must be increased in unison. However, for a given set of magnets, there are limits to the extent of possible variation of the field while maintaining the required field quality. It is therefore necessary to have a cascade of accelerators, each more powerful than the preceding one. The protons start on their journey with a modest beginning, are accelerated part way, then transferred to the next machine, and so on to their ultimate destination, the collider ring. At Fermilab, for example, there are four major elements in the sequence, a linear accelerator that accelerates the protons to a kinetic energy of 0.2 GeV (1 GeV = 1 billion electron volts), then a rapid-cycling booster that brings their energies up to 8 GeV. From the booster, the protons are injected into a main ring of conventional magnets where they are accelerated to 150 GeV (0.15 TeV) before transfer to the superconducting ring for a boost to the final energy of 1 TeV. One possible cascade of accelerators for the SSC is shown in Figs. 1-2 and 1-3. The part of the cascade up to the collider ring is usually called the injector, even though each member of the cascade is an accelerator in its own right.

B. DESCRIPTION OF THE SSC

The proposed SSC as described in the Reference Designs Study (RDS) consists of four basic components: 1) an injector complex of three cascaded accelerators roughly similar to Fermilab's Tevatron, in which protons will be accelerated from rest to about 1 TeV; 2) the collider ring, whose circumference will be between 60 and 100 miles, depending on the final magnet type selected; 3) the experimental areas; and 4) the campus/laboratory area. This section describes these components in greater detail.

1. The Injector Facility

As already described, machines like the SSC require a cascade of accelerators. In the model of the RDS, the injector consists of a cascade of three separate accelerators, a linac, a low-energy booster, and a high-energy booster, each accelerating the protons to ever higher energies while maintaining their bunched beam structure. Components of the injection system will be buried at least 20 feet underground and in the RDS were located close to the campus-laboratory area. Two prime performance objectives apply to the SSC injector: 1) its beam must have a concentrated high flux of protons to achieve the specified beam intensity in the collider ring; and 2) its final energy must match the lowest energy permitted by the magnetic field of the collider ring in order to prevent beam loss at injection.

The first step of the injection system is a linear accelerator (linac) in which the protons are generated in an ion source and accelerated from rest to energies as high as 1 GeV. The linac would be approximately 750 feet long and consist of many radio-frequency (rf) cavities in line. From such a linac, the protons are transported through a beam pipe into a low-energy booster (LEB). In the RDS, the LEB is designed to raise their energy to 70 GeV. Such a synchrotron would be about 0.7 miles in circumference, and would utilize conventional magnets.

From a 70-GeV LEB synchrotron, the last step of the injection process would be a high-energy booster (HEB), in which the protons have their energy raised to approximately 1 TeV, the minimum energy necessary for injection into the collider ring. The high energy booster is itself an accelerator of impressive proportions, approximately 4 miles in circumference. It would use superconducting magnets cooled by liquid helium in a system similar to the operating Tevatron at Fermilab.

The conventional facilities of the injector complex include an enclosure for the linac, an LEB tunnel roughly 0.7 mile in circumference, with six power supply junctions, one injection and two extraction sections. The HEB tunnel is about 4 miles in circumference with six power-supply buildings, one building for the refrigeration system, two injection areas, one rf area, and two extraction/abort areas. Figure 1-3 shows an arrangement of the injector complex and the collider ring, and Fig. 1-4 is an aerial perspective of a possible site layout.

2. The Collider Ring

The most prominent single element of the SSC is the collider ring, a circular tunnel whose cross-section has a diameter of about 9 feet and a circumference (depending on the final design chosen) from 60 to 100 miles. Inside the tunnel are two rings of superconducting bending (dipole) and focusing (quadrupole) magnets, which steer and confine two beams along approximately circular orbits. The bunches of 1-TeV protons received from the high energy booster are apportioned between the two collider rings and accelerated in opposite directions. For most of the circumference, the two beams travel in separate, parallel vacuum chambers, side by side or one above the other. At six locations the counter-rotating beams, having been focused to less than one thousandth of an inch in transverse dimensions, are brought into collision. The two beams are directed to collide almost head-on in the heart of the particle detectors, which surround the beams at the interaction points.

As discussed in the introduction, the circumference of the collider ring of the SSC will depend on the strength of the dipole magnets chosen to bend the trajectory of the protons. A tunnel of 60 miles in circumference would be required with the stronger magnets (about 6 tesla [T], or 60 kilogauss). An even larger circumference, 100 miles, would be needed if lower field (3-tesla) magnets are chosen. The decision, expected by the end of September 1985, about the kind of magnets to be used in the final design of the SSC will be based on the results of development efforts now in progress at several accelerator laboratories around the country.

Despite their differences in circumference, the alternative collider ring designs share certain basic features. For example, a specific ring design might be planned as a circle (actually, a combination of short straight sections and arcs approximating a circle) but might also be conceived as a racetrack shape if the chosen site proves more suitable for that type of configuration. The six regions at which the beams intersect may be widely and symmetrically spaced around the ring, or they may be grouped at two or three regions. In the most convenient accelerator designs the collider ring lies in a plane. The plane can be horizontal or tilted slightly (not more than one degree) to accommodate a slope on the site.

Basic to the SSC, whatever its size, are the existence of six experimental regions containing straight sections where beams collide and experiments take place. In addition, there are special utility regions for beam injection, beam extraction and abort, and the radiofrequency acceleration systems.

In addition to the technical components of the SSC accelerator itself, the project will contain a number of structures and facilities that involve conventional design and construction techniques. For example, in one of the designs of the RDS, twelve buildings, equally spaced around the collider ring, would house the services needed for the power supplies and refrigerators. Additional buildings would be provided for injection/extraction and for rf equipment.

3. The Experimental Areas

The experimental areas will be designed to be at six interaction regions around the collider ring circumference. At each developed area, enclosures will be provided at beam level and support buildings at the surface. At the beam level are the collision hall and the access hall enclosures. A typical collision hall with a height of 50 feet is envisioned to provide a central gallery approximately 70 ft by 70 ft, with a 45 ft by 45 ft gallery at each end along the beam direction. In detailed design each hall may be different in order to adapt it to the local site condition and to its intended use. A tunnel by-passing the experimental area makes it possible to detour equipment around the collision hall and to convey the tunnel services.

A subterranean access hall at each experimental area will provide assembly areas. Because of the enormous weight of individual detector components and their number, a relatively thick floor with steel plate might be used as the common floor for the collision and access halls.

A staging building above the access hall will provide space for the experimental teams to make a sub-assembly of their experimental apparatus and to maintain their equipment. A 300 ft by 120 ft building would contain workshops, offices, a light-duty laboratory, and counting rooms. An overhead crane in the staging hall would permit work at either the staging level or the access hall below.

4. The Campus Area

The campus complex may consist of fifteen or more buildings clustered in four major groups -- central laboratory buildings, industrial buildings, warehouses, and auxiliary support buildings.

Central laboratory buildings provide office and laboratory space for administrative and technical personnel. One building might contain all of the major offices of the facility and light laboratories for the development and testing of electronic components. It would also include control rooms, an auditorium, computing facilities, a main cafeteria, a series of conference rooms, and a small infirmary for emergency medical needs. Figure 1-5 is a conceptual rendering of such a building.

Industrial buildings will house limited component assembly activities and associated offices. Warehouses serve as receiving and storage facilities. The auxiliary support buildings -- fire, site patrol, rescue and vehicle storage buildings provide services to the entire complex.

C. ESTIMATED COST AND SCHEDULE

It is expected that the actual construction of the SSC could be accomplished in about six years, which would mean completion in early 1994 if construction were to begin late in 1987. In the RDS, the cost for the construction of the accelerator facilities was estimated to be from $2.7 to $3.1 billion (FY 1984 dollars), depending on the magnet design chosen. The conventional construction represents approximately one-third of this cost. The total cost including the preconstruction R & D, the cost of the detectors, and other pre-operating costs for the facility, is about $4 billion (FY 1984 dollars). Savings on technical components may come about through optimization of designs, economy of scale in production, and improved techniques of magnet manufacture.

Site characteristics will have a direct influence on underground construction, which represents the largest single element of the conventional facilities cost. Choice of a site amenable to rapid tunneling techniques is desirable because it will contribute significantly to cost and schedule optimization. Additional site-related construction elements that will affect cost and schedule are the availability of:

- The site itself;

- Existing structures and access roads;
- Adequate utilities;
- Construction materials and labor.

D. ENVIRONMENTAL IMPACT AND RADIATION SAFETY

It is intended that the environmental impact of the SSC upon its site be minimal. As already discussed in the Introduction, apart from the occasional cluster of buildings above the ring and the larger concentrations at the injector and the separated interactions regions, the landscape will show negligible signs of the working accelerator below ground. The collider tunnel will be buried sufficiently deep to contain the small amount of stray radiation that is produced by machines of this sort. Just as at SLAC in California, DESY in Germany, Fermilab in Illinois, or CERN in Switzerland, the local population will live in complete harmony and safety with the laboratory. Even in the immediate neighborhood of the SSC, the radiation exposure will be quite small compared to that occurring from cosmic rays and other natural backgrounds, and will be below the minimum values set by appropriate agencies. During operation, protons traveling in the evacuated beam pipe produce no radiation that leaves the tunnel. The primary source of radiation will come from the particle interactions being studied in detectors at the interaction regions. Most such radiation will be absorbed internally by the detectors and will not even reach the walls of the tunnel, much less get to the surface.

In the event of a malfunction of the accelerator or a natural occurrence such as an earthquake, the beam would be promptly extracted and absorbed in a specially-prepared isolated area. In the unlikely event that the beam was accidentally lost somewhere around the ring, the momentary radiation appearing outside the earth shield would be small. After such a loss of beam, the remaining particles would be promptly removed from the SSC and produce no more radiation.

It should be emphasized that the operation of a particle accelerators is very different from that of nuclear fission reactors. An accelerator contains essentially no inherent source of radioactivity that could be released accidentally. The source of energy to accelerate particles is obtained from the same commercial electrical power grid that one taps for household appliances. Just as when an electric toaster is unplugged there is no long-term fire hazard from it, so when the SSC is off there is no potential for creation of new radiation. Like any accelerator, the SSC has within its shield some short-lived residual radiation coming from unstable nuclei created in the process of containment of the primary and secondary particles. This low-specific-activity radiation is confined to the tunnel walls and the earth in the immediate vicinity of the tunnel. It decays rapidly and causes no hazard to anything on the surface.

E. RECENT CHRONOLOGY OF THE PROJECT

Summer 1982: Summer study of the American Physical Society's Division of Particles and Fields, was held at Snowmass, Colorado. An in-depth examination of the idea of a 20-TeV/beam proton-proton collider resulted from this meeting. Strong widespread support for the physics goals of such a collider emerged.

February 1983: A week-long workshop was held at the Lawrence Berkeley Laboratory (LBL) in California to consider detector problems for a high energy, high luminosity hadron-hadron collider.

March 1983: A workshop was held at Cornell University in Ithaca, N.Y., to consider technical and cost questions associated with construction of a 20-TeV/beam hadron-hadron collider.

July 1983: A subpanel of the High Energy Physics Advisory Panel (HEPAP), convened early in 1983 to consider the future high energy facilities in the United States, recommended construction of a new high energy, high luminosity, hadron collider. This recommendation, unanimously endorsed by HEPAP as its "highest priority" for high-energy physics, was transmitted to DOE.

Fall 1983: DOE initiated preliminary R & D for the SSC. Hearings were held before the House Science and Technology Committee concerning redirecting resources toward the SSC R & D.

December 1983: The Reference Designs Study was chartered by the directors of the U.S. high-energy accelerator laboratories with the energy and luminosity goals defined.

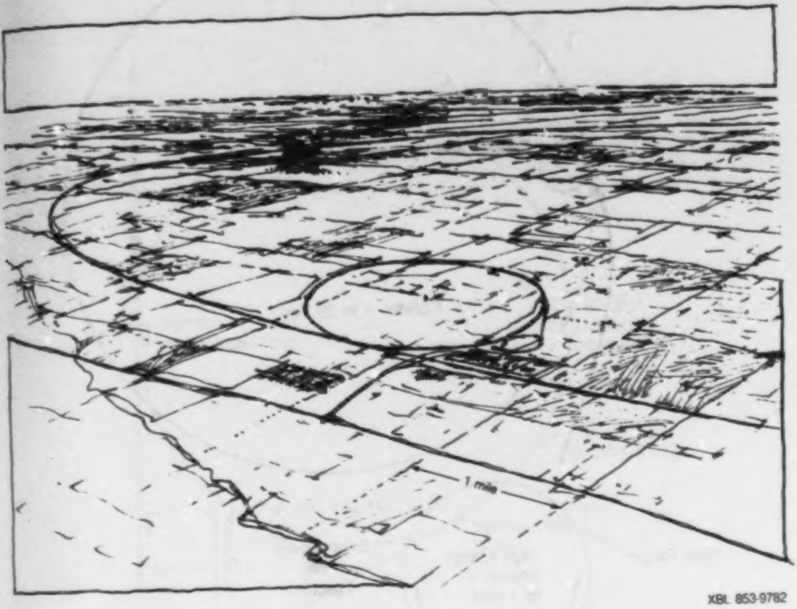
March 1984: DOE assigned responsibility for oversight of the national SSC effort during the R & D preconstruction phase to the Universities Research Association.

Spring 1984: The Reference Designs Study was held at LBL with about 150 participants. It was concluded that a 20 TeV on 20 TeV proton-proton collider is technically feasible. The Study, also containing construction cost estimates and schedules, was extensively reviewed by DOE personnel and their consultants.

Summer 1984: Initiation of the Phase I R & D program for the SSC was approved by the Secretary of Energy. Extensive work on model magnets for the SSC was already underway at Brookhaven National Laboratory, Fermilab, Lawrence Berkeley Laboratory, and the Texas Accelerator Center.

Fall 1984: Formation of the Central Design Group (CDG), headquartered at the Lawrence Berkeley Laboratory. The CDG has been charged with directing and coordinating all of the SSC R & D work nationwide.

Spring 1985: SSC Siting Parameters Document submitted to the Department of Energy.



XBL 853-9782

Fig. 1-1.

Aerial view of median site illustrating the scale (see 1-mile marking) of the SSC facility. The collider ring perimeter is only noticeable when the tunnel approaches the surface. The injector and campus area are visible in the center. Access roads to nearby population centers are clearly visible.

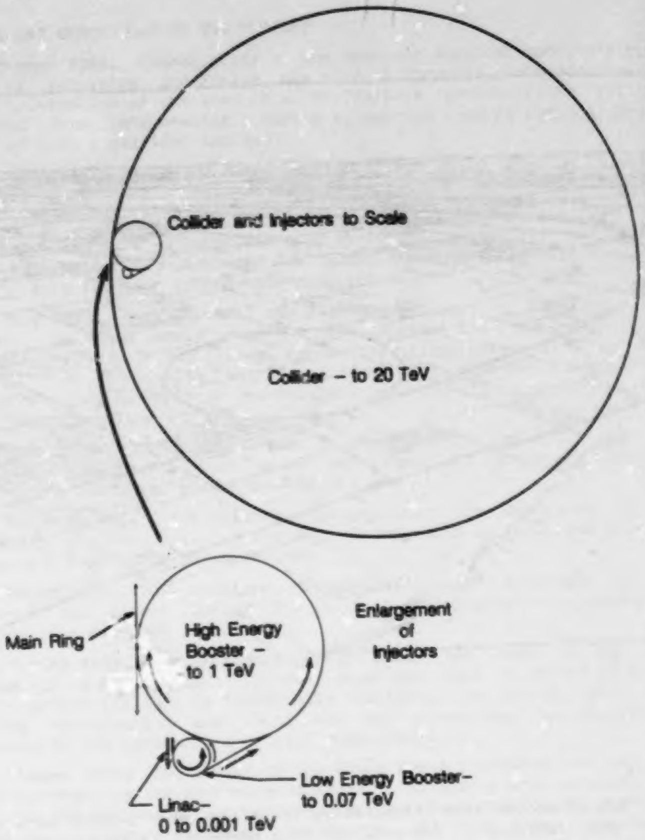

Collider and Injectors to Scale
Collider – to 20 TeV
Main Ring
High Energy Booster – to 1 TeV
Enlargement of Injectors
Low Energy Booster– to 0.07 TeV
Linac– 0 to 0.001 TeV

Fig. 1-2.

Layout of the SSC indicating the injector complex and the collider ring where protons are accelerated to 20 TeV in counter-rotating bunches that collide at six points around the circumference.

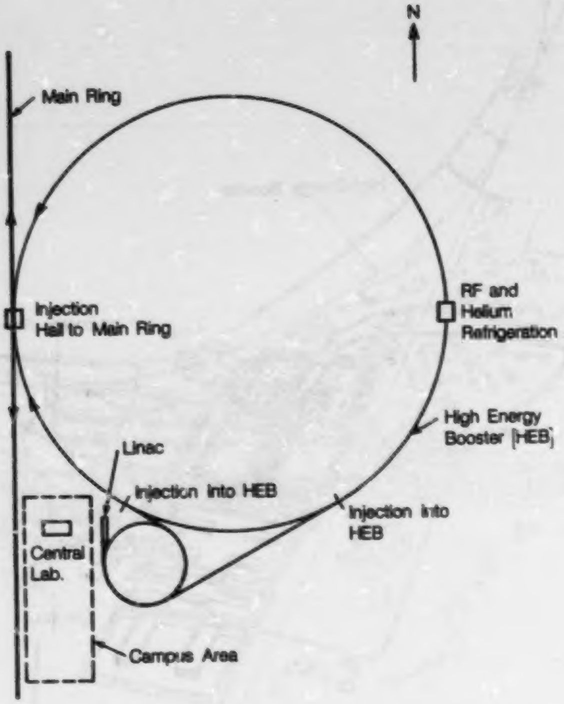

N
Main Ring
Injection
Hall to Main Ring
RF and
Helium
Refrigeration
High Energy
Booster (HEB)
Linac
Injection into HEB
Injection into
HEB
Central
Lab.
Campus Area

Fig. 1-3.

Arrangement of the injector complex adjacent to the collider ring, as depicted in the Reference Designs Study.

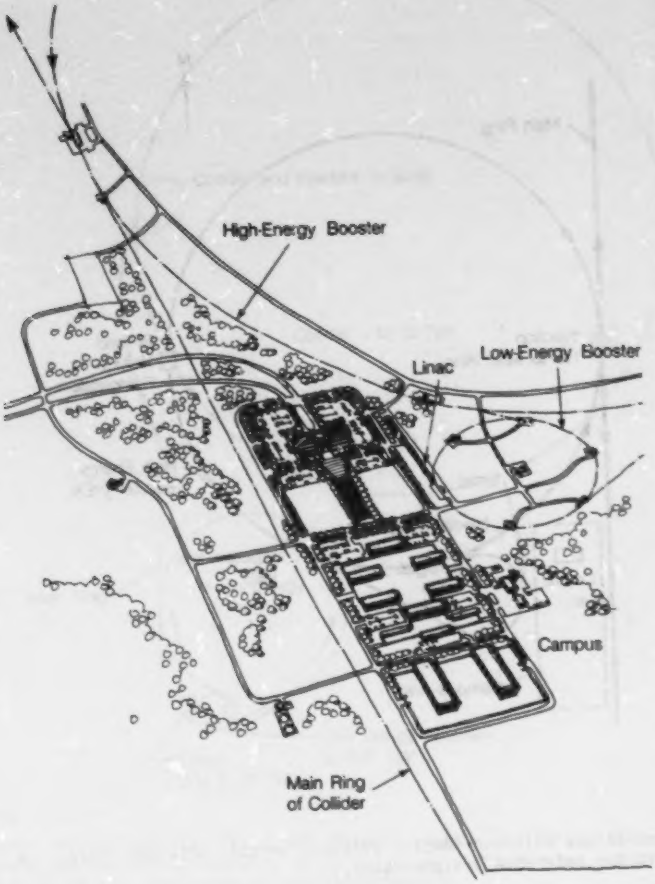

High-Energy Booster
Linac
Low-Energy Booster
Campus
Main Ring
of Collider

Fig. 1-4.

Aerial view of the campus revealing its compact arrangement and its proximity to the injector facility.

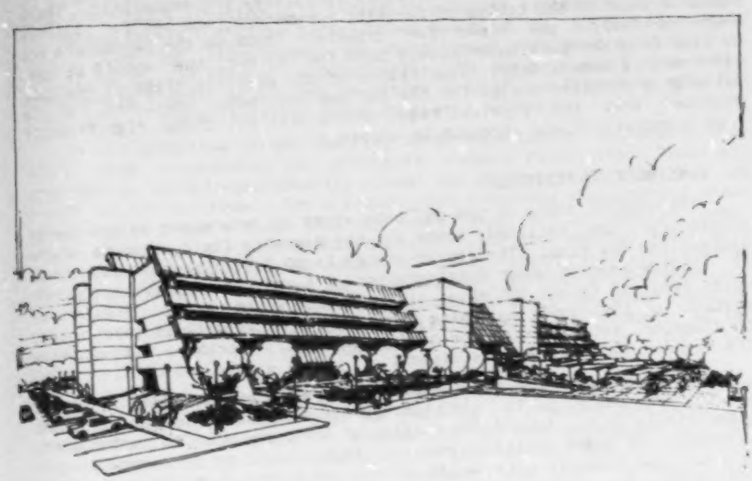


Fig. 1-5.

The south facade of the central laboratory building as envisioned in the Reference Designs Study.

PART II. FEATURES OF THE SSC FACILITY

This chapter summarizes requirements envisioned for the proposed SSC facility. The information used is derived from the Reference Designs Study (RDS) with attention given to the two magnetic field strengths for the bending magnets currently being considered. After a brief description of the scope of the collider ring, the main technical features of the RDS accelerator and laboratory facilities are enumerated. These features lead to the tables of facility parameters, one set for 6-tesla magnetic field, the other for 3-tesla. Because the parameters are derived from the particular models used for the RDS, they should be considered only approximate, illustrative of one possible class of designs. Although a detailed design for the SSC has not been completed, it is believed that the physical requirements will not change significantly once a magnetic field strength is chosen.

A. CONSTRUCTION FEATURES

The overall scale of the SSC Laboratory is determined by the energy chosen for the collider beams and the magnetic field strength of the magnets for the ring. The design energy is 20 TeV. For the two types of bending magnets under consideration, 6 T and 3 T, approximately circular rings of 60 and 100 miles circumference would result. The cross-section of the tunnel enclosing the collider rings will be about 9 feet in diameter, determined by the need to install, operate, and maintain the magnets and associated equipment.

Radiation shielding for the collider requires 20 feet of earth around the tunnel. In addition, particles (muons) that are produced tangentially (i.e., toward the outside of the ring) must be attenuated. Absorption of these particles requires that a corridor be reserved adjacent to, and radially outside the shield, including space 25 feet above and below the plane of the accelerator. Wells and other penetrations can exist within this corridor but sustained human occupancy would not be permissible. The overall width of the radiation zone is 700 feet in the 6-T configuration, and 350 feet in the 3-T case, as shown in Fig. 2-1.

Access to the tunnel and structures for equipment will be provided at various locations around the perimeter. Twelve major service areas are provided for refrigerators, power supplies, and access shafts in the 6-T case, and twenty four in the 3-T case, uniformly distributed around the ring. The service locations require power for the helium compressors, power supplies, and the nitrogen liquefaction systems. Sufficient industrial cooling water to reject the heat from the compressors and the air-conditioning associated with the technical systems must be available. Land area must be provided on the surface at each of the service locations for a building or buildings to house the technical systems, along with space for maintenance purposes. A storage yard for helium and nitrogen gases must also be provided. The total area requirement at each of these locations is approximately 30 acres. Between these locations additional shafts are provided that serve for tunnel ventilation and also provide emergency exit. The total area needed for both the service areas described above and the necessary infrastructure such as roads, utility and communication runs is about 800 acres for the 6-T case and 1500 acres for the 3-T case.

In the RDS, three designated locations around the collider ring provide facilities for injecting beams clockwise and counterclockwise into the machine, for accelerating the beams, and for ejecting the beams from the machine. At each of these locations, an area of approximately 10 acres will be required to house the associated equipment. An ejected beam at an abort location will travel in a tunnel tangential to the ring for approximately 0.6 miles before being absorbed in a shielded beam dump. Like the ring tunnel, the abort tunnel must have a cover of 20 feet of earth. An area of approximately 80 acres beyond the dumps encompassing a width of 50 feet on either side of the beam dump axis for a distance of approximately 3 miles must be provided.

At six locations around the ring large experimental halls are provided, each accompanied by extensive support facilities. These six areas may be spaced equidistantly around the perimeter or clustered in groups of two or three. For a design with clustered experimental areas the perimeter takes a shape that is more oval or in another case, slightly triangular, rather than circular. The experimental areas will each require approximately 60 acres of land, which will include an assembly and control building for the detector, machine shops, food services facilities, parking, space for expansion, etc. The power requirements and industrial and low-conductivity water requirements at the experimental areas will be approximately the same as for the refrigerator/power supply areas.

The campus area and the central laboratory building will be the primary focal point for work at the SSC. It is expected that about 500 acres of land will be needed to accommodate the 3000 people who will use the campus. Also in the campus area are the injector facilities. This will be a group of accelerators used to boost the beam to sufficient energy to be injected into the collider ring. In the RDS, the injector consisted of a linear accelerator (linac), and two circular booster accelerators. These are substantial accelerators in their own right, and altogether require a space of about 1500 acres.

B. TABLE OF TECHNICAL FEATURES OF THE SSC

The major technical features of the SSC Reference Design are as follows:

Injector

Linac	
Energy	1 GeV
Length	750 ft

Low-Energy Booster	
Energy	70 GeV
Circumference	0.7 mi
Conventional Magnet Peak Field	2 T
No. of Service Buildings	6

High-Energy Booster	
Energy	1 TeV
Circumference	4 mi
Superconducting Magnet Peak Field	5 T
No. of Power-Supply Service Buildings	6
No. of Helium Refrigerators	1
No. of RF System Service Buildings	1

Collider

Peak Bending Field	**6 T**	**3 T**
Beam Energy	20 TeV	20 TeV
Accelerator Circumference	60 mi	100 mi
No. of Counter Rotating Beams	2	2
No. of Power-Supply Service Buildings	12	24
No. of Helium Refrigerator Systems	12	24
No. of Nitrogen Liquefier Systems	2	4
No. of Injection Conjunctions	2	2
No. of RF Accelerating Systems	2	2
No. of Abort Systems	2	2

Experimental

No. of Interaction Regions (equally spaced, or clustered in two or three areas)	6	6

. TABLE OF FACILITY PARAMETERS FOR THE SSC USING 6-T MAGNETS

This table summarizes the basic physical parameters of the SSC for he 6-T peak bending field configuration. The requirements are derived rom the RDS.

1. General		
Magnetic Field		6 T
Circumference of the Collider Ring		60 mi
2. Area		
Campus		500 acres
Service Areas		400
Site Infrastructure		400
Injector		1,500
Collider		5,000
Experimental Areas		500
Total		8,300 acres
3. Above-Ground Buildings (gross area)		
Campus Buildings		
Central Laboratory Building	365,000 sq ft	
6 Assembly Buildings	168,000	
3 Shops Buildings	30,000	
2 Warehouses	80,000	
Other Buildings	24,000	
Subtotals		667,000 sq ft
Injector Service Buildings		56,000
Collider Service Buildings		112,000
Experimental Area Buildings		225,000
Total		1,060,000 sq ft
4. Below-Ground Enclosures		
Injector		28,000 ln ft
Collider (excluding experimental areas)		317,800
Experimental Areas		2,200
Total		348,000 ln ft
5. Utilities (average except as noted)		
Average Electric Power Demand		106 MW
Peak Electric Power Demand		160 MW
Heat Rejection Load		306 MBtu/hr
Cooling-Tower Make-Up Water		780 gal/min
Potable Water		310 gal/min
Pond Make-Up Water		130 gal/min
Irrigation Water		300 gal/min
Fire-Protection Water Storage		2.8 Mgal
Sewage-Plant Effluent Discharge		91,000 gal/day
Solid-Waste Disposal		30,000 cu yd/yr
Heating Rate (coldest month)		55,000 MBtu/hr
Telecommunications		200 trunks

D. TABLE OF FACILITY PARAMETERS FOR THE SSC USING 3-T MAGNETS

This table summarizes the basic physical parameters of the SSC for the 3-T peak bending field configuration. The requirements are derived from the RDS.

1. General		
Magnetic Field		3 T
Circumference of the Collider Ring		100 mi
2. Area		
Campus		500 acres
Service Areas		800
Site Infrastructure		700
Injector		1,500
Collider		4,300
Experimental Areas		500
Total		8,300 acres
3. Above-Ground Buildings (gross area)		
Campus Buildings		
Central Laboratory Building	365,000 sq ft	
6 Assembly Buildings	168,000	
3 Shops Buildings	30,000	
2 Warehouses	80,000	
Other Buildings	24,000	
Subtotals		667,000 sq ft
Injector Service Buildings		56,000
Collider Service Buildings		169,000
Experimental Service Buildings		225,000
Total		1,117,000 sq ft
4. Below-Ground Enclosures		
Injector		28,000 ln ft
Collider (excluding experimental areas)		525,800
Experimental Areas		2,200
Total		556,000 ln ft
5. Utilities (average except as noted)		
Average Electric Power Demand		117 MW
Peak Electric Power Demand		196 MW
Heat Rejection Load		303 MBtu/hr
Cooling-Tower Make-Up Water		775 gal/min
Potable Water		310 gal/min
Pond Make-Up Water		130 gal/min
Irrigation Water		300 gal/min
Fire-Protection Water Storage		2.8 Mgal
Sewage-Plant Effluent Discharge		91,000 gal/day
Solid-Waste Disposal		30,000 cu yd/yr
Heating Rate (coldest month)		55,000 MBtu/hr
Telecommunications		200 trunks

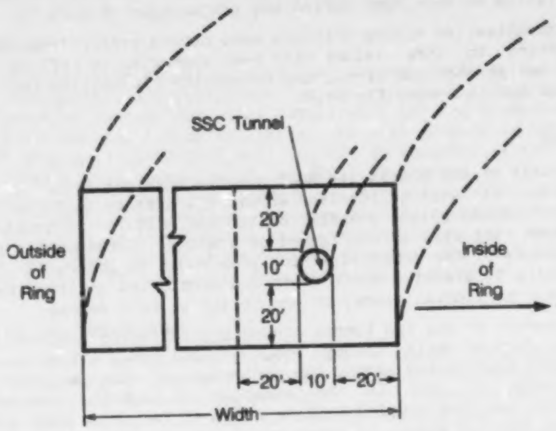

SSC Tunnel
Outside of Ring
Inside of Ring
20'
10'
20'
20'
10'
20'
Width

Fig 2-1.

This drawing illustrates the volume of space and the tunnel that must be under SSC control. The width is 700 feet for the 6-T configuration and 350 feet in the 3-T case.

PART III. SSC SITING CRITERIA

Earlier parts of this document have described the proposed SSC, its basic physics parameters, technical and construction features. Part II, in particular, quantifies the major SSC parameters that form the basis for the siting criteria described below. These siting criteria have been developed to assist in the process of site identification. The criteria were derived after thorough examination of desirable site characteristics as developed during the preparation of Part IV.

The quantitative siting criteria used herein differ from the Part II parameters in that values have been augmented to reflect possible alternate design configurations, and to provide flexibility for adaptation of the SSC to a specific site.

A. SETTING

The scale of the SSC is its most notable physical feature. In the region where it will be located, an overall area up to 40 by 50 miles would be influenced by the presence of the SSC. It is envisioned that the collider ring will be configured on a plane. Consequently a desirable topography of the proposed siting area would be generally flat or gently sloping to minimize shaft depth and permit the collider tunnel to be built on a horizontal plane, or one tilted up to 1 degree.

Independent of the two tunnel circumferences being considered, the whole SSC complex will occupy about 11,000 acres (17 square miles) appropriately distributed around the perimeter of the collider in a manner similar to that of the examples in Part II. Permanent and exclusive SSC use (fee simple) will be required for about 5000 acres for the campus, service areas, injector area, and experimental areas. This includes at least 1700 acres providing an allowance for SSC adaptation to the site, laboratory growth, and possible future external beam lines for experiments or injection into other research devices.

With respect to the collider, in areas where the tunnel is buried much more than 20 feet underground and where there are no SSC surface buildings over the tunnel, land could be shared with others with priority of use (by easements) granted to the SSC. To maintain the integrity of the tunnel and SSC operations, a volume of below-ground space around the tunnel must be under SSC control. This volume was described in Part II and shown in Fig. 2-1. This configuration leads to a horizontal projected area at the surface of about 5000 acres. In addition, right of way easements for roads, utility and communications runs will bring the total up to 6000 acres. For a shallow very flat site, all the SSC tunnels would be constructed by cut and fill methods. This would require that permanent and exclusive use (fee simple) be granted to the SSC for all segments of the project, leading to a requirement for the entire 11,000 acres.

The band of land totalling up to 17 square miles would encircle a large area of several hundred square miles that would be unaffected, allowing continued use and habitation. The SSC will be planned, designed, constructed, and operated as a Federal installation. It will be important to know the cost of land acquisition, if any, to the Federal Government, and the value of any donations of land and services that may be offered.

The size of the collider may cause it to pass through several local jurisdictions. The successful construction and safe operation of the facility require that provision be included, through enabling legislation, if necessary, for the SSC to be built and operated under a single, uniform set of codes and health, safety, and environmental rules.

B. ENVIRONMENT

The proposed site should be such that the SSC facility can be positioned, constructed, and operated in an environmentally acceptable way. The Department of Energy (DOE) will comply with the requirements of the National Environmental Policy Act (NEPA) and will prepare an Environmental Impact Statement (EIS) that will include an analysis of the impacts of construction and operation of the SSC. Environmental characterization information provided by a proposer would be used by DOE in preparing an environmental evaluation. Because the environmental characterization data contained in proposals might be used by DOE in preparing a full EIS, proposers should be encouraged to submit the best data available; four seasons of monitoring data are highly desirable.

C. GEOLOGY AND TUNNELING

Because major portions of the SSC will be built underground, the cost and efficiency of underground construction and tunneling are important considerations in selecting the site. For construction purposes, relatively uniform geological characteristics are desirable to permit large contiguous segments to be built using a common construction methodology. For example, if a tunnel in rock is proposed, rock with few fractures or discontinuities and sufficient compressive strength to permit unsupported tunneling would be most desirable. Structural features such as faults, shear zones, buried valleys, and deep or shallow subsidences are to be avoided to the maximum extent possible. In areas where cut-and-fill construction or embankments are proposed, conditions that could result in settlements and ground movements, including slope failures, should be avoided. Soft soils, such as certain clays, present difficult tunneling, excavation, and foundation conditions and should be avoided. Bearing capacity for foundations in the experimental areas (halls) should be sufficient to minimize differential settlement between halls and the adjacent tunnels. Typical floor loadings in the experimental areas are estimated as 6 tons per sq ft with total loads of up to 10,000 tons. Elsewhere loading is light, less than that exerted by the removed material.

Ground water may pose significant underground construction problems in pervious soils or where rock tunnels traverse water-bearing faults or shear zones. As a practical matter, tunnel construction in unconsolidated granular soils containing ground water with a head greater than about 100 feet is very difficult and should be avoided to the maximum extent possible. Local pervious structural features in rock can usually be stabilized, but tunneling through great lengths of pervious material would be time consuming and costly.

Properly designed underground facilities are generally insensitive to seismic effects. In a seismically active area provisions are required in the design of certain surface structures, of underground experimental halls, and by the provision of restraints for installed underground equipment (magnets, cryogenic system, experimental detectors, etc.). A seismic event involving rupture along a fault crossing any portion of the facility cannot be mitigated, and thus a site crossing an active fault is unacceptable.

D. COMMUNITY RESOURCES

Communities near the proposed site should be sufficiently large to support up to 10,000 people (3000 staff and visitors and their families) attracted by the construction and operation of the proposed SSC. Although it is anticipated that a large percentage of Laboratory employees will be drawn from adjacent communities, a substantial number of new families must be drawn from elsewhere to work at the new SSC laboratory. They will require suitable housing, schools, shopping, and related facilities. A significant growth of established and new communities may be required. Furthermore, temporary or transient quarters, such as hotels, motels, and apartments will be needed to accommodate a large number of visitors, including scientists, government officials, and others participating in the activities of the laboratory. It is thus desirable that the laboratory facilities should be within a reasonable commuting time of existing or potential communities.

A major airport facility, supported by public transportation, rental cars, and related services, should be readily accessible to the Laboratory. The existing or projected regional transportation network should have the capacity to serve the SSC needs. Ready access to the entire laboratory facility from local communities and from outside the region is essential. Interstate-quality highways and all-weather roads for public and private transportation capable of carrying major construction loads as well as commuter traffic to and from the laboratory will be expected to exist or be provided.

Nearby educational facilities will also be important. Good quality primary and secondary schools will be essential for the families of the staff. Universities, colleges, and institutes in the area could contribute to its desirability by providing a source of technical staff and opportunities for continuing education for the staff.

To attract the needed scientific staff, the surrounding area should offer sufficient quality and quantity of social and cultural opportunities. Recreational resources within the region are valuable in making the nearby communities desirable.

For economy it is desirable that industrial and construction resources be drawn from the surrounding communities whenever possible.

E. UTILITIES

Water availability is a significant consideration in evaluating site suitability. A potential need for up to 2000 gal/min of water exists, of which 500 must be potable. For industrial purposes the quantity and quality of water available will dictate the type of cooling system to be provided, which in turn will affect the associated power demand and the facility operating cost. The required industrial water flow rate that would permit the most efficient use of electrical power is about 1500 gal/min. The lack of water would increase the power demand significantly. Sites capable of supplying as little as 500 gal/min. of industrial water can be considered but will require the use of about 25% more power for forced-air cooling.

The amount of electrical power required to support the operation of the SSC will depend on the type of cooling system used. As noted above, sites with abundant available cooling water will require less electric power than will those with limited amounts of available water. The peak power requirement for the SSC, based on desirable climatic conditions and on the use of a typical industrial-water evaporative cooling system, will be about 200 MW. If an air-cooled system is used, the peak electrical power demand for the SSC site is anticipated to be about 250 MW.

High stability and reliability of the electrical grid serving the SSC is essential. Generating capacity should be at least 12 times rated peak site load. It is highly desirable that power be provided by two separately routed feeder lines each connected to different points on the grid(s) such that essential loads are maintained in the event either line is out of service. Long power outages (more than 30 minutes duration) will result in a significant expense through loss of cryogenic fluids from the magnets. Outages of a few seconds or less can cause significant interruptions to the laboratory program. More than two unanticipated outages per independent feed per year on the average would have a considerable negative impact on maintaining machine operations.

A fuel supply compatible with the climate is necessary. For example, a local fuel-delivery system capable of providing at least 60,000 MBtu/hr should be available to serve the laboratory if the coldest month at the site corresponds to 900 degree-days.

F. MAN-MADE DISTURBANCES

Because colliding-beam research depends upon two small beams accurately hitting each other head-on for many hours, stability of operation is important. Sources of noise or vibration such as those produced by airplanes, highway and railroad traffic, or industrial activities could be disruptive and must be examined.

The beams are sensitive to ground motion in the frequency range from a fraction of a hertz to several hertz. At about 3 hertz there is a resonant beam response to the ground motion. However, by using a feedback system, ground motion of the order of 0.01 mil (rms averaged over the site) amplitude in this frequency range can be controlled. A larger ground motion may require a feedback system stronger than envisaged, and therefore would be undesirable.

G. CLIMATE

Climate will have a direct influence on SSC operational cost and efficiency. Average temperature and humidity levels will affect heating and cooling system capacities and operating costs. Adverse weather will also affect operational productivity. Summers with low humidity and few severe storms and winters with low accumulations of snow would be most advantageous. A seasonal average mean temperature of 35°F or greater in winter and an average mean temperature of 80°F or less in summer would represent a desirable climate range. Similarly, a relative humidity range of 25 to 70 percent, coincident with the summer average mean temperature stated above, would be desirable. The economic effect of local climate on operation and construction must be taken into account.

H. COST AND SCHEDULE

Economies in construction cost and schedule are important factors to consider and plan for at the SSC. The cost and time to construct the SSC will be strongly dependent upon site geological, geohydrological, and climatic conditions. The tunnels and accesses are major cost elements in the project, and existing experience with underground construction in the region of the site should be noted.

Annual operating costs, including those based on local wage scales, utility rates, transportation charges, etc., must be considered. Operating and construction costs must be evaluated over the long term to achieve an optimum balance. Substantial savings can be achieved through preferential utility rates and road maintenance concessions.

Donation of land for the site and availability of existing buildings and facilities in the vicinity would affect favorably both cost and schedules.

PART IV. INFORMATION NEEDED ABOUT PROPOSED SITES

This part of the document addresses the kinds of information needed about a proposed site in order to assess its suitability. The information needed is organized into eight sections corresponding to the criteria sections used in Part III.

The sections have a consistent format. The opening paragraphs of each section describe and explain some of the important aspects of the information that would be needed about proposed sites. Following these paragraphs are itemized statements that define the needed information. This format has been chosen in order to clarify as much as possible the particular aspects of each issue that are judged most important.

Selected information topics have been identified as necessary for a first overall assessment of the strengths and weaknesses of any site. It is envisioned that DOE might ask that these be addressed in a preliminary response from the proponents of a site. The items that have been recommended for preliminary attention are enumerated below and marked with asterisks (*) in the text.

A. Setting
1.(ii)., 1.(iii)., 2.(ii)., 2.(iii)., 4.(i).

B. Environment
1.(i)., 2.a.(i)., 3.a.(ii)., 3.b.(ii)., 7.(ii).

C. Geology and Tunneling
1.(i)., 2.(i)., 3.(i)., 4.(i)., 5.(iii).

D. Community Resources
1.(i)., 2.a.(i)., 3.a.(i)., 3.b.(i)., 5.(i).,
6.(i)., 6.(iii)., 7.(i).

E. Utilities
1.(i)., 2.(i)., 3.a.(i)., 3.b.(i).

F. Man-made Disturbances
1.(i)., 2.(i).

G. Climate
1.(i)., 2.(i).

H. Cost and Schedule
1.(ii).

A. SETTING

1. General

Because the SSC will be such a large facility, it is likely to be located near a number of communities. For each proposed site, an evaluation of possible interferences with existing man-made facilities should be addressed, (e.g., residential, commercial, agricultural, industrial or other developed areas that could be affected by the construction or the operation of the SSC).

SSC construction could affect features such as surface-water courses, prominent geologic features, vegetation of some unique or special character, ground water used for shallow-well supplies, etc. Possible effects upon natural features by the SSC construction or operation should be assessed.

Information Needed

(i). An overall assessment of the suitability of the proposed region(s) for siting the SSC based on the general siting needs described earlier.

* (ii). An indication of how the SSC facilities could best be placed within the area(s) proposed, using a current edition of the USGS 7-1/2 minute or similar quadrangle map sheets as a base.

* (iii). A narrative describing the proximity and extent of relevant man-made and natural features of the region that have a bearing on the siting.

(iv). A description of the measures that might be taken to deal with interferences with existing man-made or natural features.

2. Land Commitment

The lands required to be committed for the SSC by acquisition or easements were defined in Part III. Various options might be used singly or in combination to achieve the objective of Federal jurisdiction over the lands. At minimum, however, the United States must obtain fee simple title to those areas where surface facilities are to be located. For the land commitment option or options proposed, constraints, pending actions, issues of possession and use, concerns for existing uses and improvements, and related cost, if any, or time impacts would have to be identified.

Information Needed

(i). A site land area commitment proposal, taking into account the objectives, issues, and concerns set forth in Part III.

* (ii). The cost, if any, to the Federal Government of obtaining the required possession and use of lands required for the construction and operation of the SSC.

(iii). A description of the issues, actions, or proceedings that must be brought to a conclusion in order to be in a position to commit the property or property-use rights as indicated, including an estimate of the time required to complete the project.

(iv). Discussion of the schedule and interface required between project, state, and Federal Government.

(v). Discussion of the degree of local awareness of the proposed land area commitment, and the degree of support or opposition likely to be encountered.

3. Institutional Setting

a. Regulations

The SSC will be a Federal facility, and the U.S. Government is not subject to many state and local requirements. Nevertheless, matters of land-use policy, zoning and the objectives of a General Plan would be affected, as would requirements and procedures for issuance of permits and licenses. Local matters such as water-rights ownership, adjudication and availability, and air-rights policies would also be affected. Issues would arise related to local administration of subsurface easements, mineral rights, and oil and gas rights.

Information Needed

(i). Specific information regarding the existing laws, regulations, policies, codes, plans, ordinances, rights, or other local statutes and jurisdictions that would be affected by the SSC or that could affect the SSC at the site proposed.

(ii). A discussion of the measures required to satisfy, mitigate or otherwise deal with the matters identified, and the time required and proposed schedule for such proceedings.

b. Taxation

Each political jurisdiction requires sources of revenue to carry out its role as set by the public. The introduction of the SSC and the commitment of substantial land areas to the Federal Government for the laboratory would have an effect on local tax revenue sources. Any local special assessment district such as irrigation, power, fire protection and public safety, schools, roads, etc., that is currently relying upon property tax revenues to meet debt obligations of the district that would be affected by the proposed Federal facilities, would need to be identified.

Information Needed

(i). An analysis of the current tax revenues, by jurisdiction, that are derived from the lands, improvements, business conducted or other taxable sources in the area or on the lands proposed for use by the national laboratory.

(ii). An indication of the position of the host state and other local bodies with regard to tax policies if considered applicable to transactions and properties involved with the construction and operation of this national laboratory.

(iii). Costs, if any, that might be borne by SSC that are related to taxation, tax policy, tax revenue, impact payments or related matters.

c. Employment Practices

Employment practices and active Affirmative Action in implementing fair employment practices within the state and the region proposed for siting the SSC are of critical concern to this project. The SSC National Laboratory will be an Equal Opportunity employer. All qualified people will be eligible for employment and there will be no discrimination because of race, color, religion, sex, national origin, age, or handicap. Affirmative action will be taken to achieve the full realization of equal opportunity.

Information Needed

(i). Evidence with regard to the current policies and history of compliance with Federal fair employment practices, with Equal Employment Opportunity statutes, and with open housing practices.

4. State and Local Government Support

As described in Parts II and III, there are a variety of services, facilities, support needs, and areas of institutional assistance where the support of state and local government will be essential to the creation of the SSC. Beyond the previously discussed concerns about setting, assistance by state and local government in securing the necessary utility services will be essential to the successful construction of the SSC.

Transportation facilities, including highways, roads, railroads, and airports, will play a key role in mobilizing for SSC construction and later operation. As discussed in Part III, a timely commitment and initiative on the part of state and local government (or other competent authority) to provide these facilities would be desirable.

There will be ample opportunities for strong and effective cooperation between local, state, and Federal agencies in bringing about the economic and scientific success of the SSC National Laboratory.

Information Needed

(i). An overall description of the nature and extent of proposed state and local government support in facilitating the siting, construction, and operation of the SSC.

(ii). A description of the state and local support that is offered in the areas of permitting and procedural assistance; securing of utility accesses and connections; and providing and/or maintaining access roads, highways or other site facilities.

(iii). Services and support that local and state government may be able to provide in assisting in the construction and operation of the SSC.

B. ENVIRONMENT

The SSC will be constructed and operated with minimal and acceptable environmental impact. The Department of Energy will comply with the requirements of the National Environmental Policy Act (NEPA) and will prepare an Environmental Impact Statement (EIS) that presents an analysis of the impacts of construction and operation of the SSC.

The siting of the proposed SSC is significantly dependent upon identification of the environmental characteristics of the immediate area and its surrounding environs. It is also very important to be able to identify the significant effects of the SSC on the environment. Evaluations need to be made by considering environmental characteristics such as land use, surface water, ecology, air quality, and historic and archaeological resources.

1. Land Use

An environmental concern with respect to land use is the identification of wetlands, prime or unique farmland as designated by the Soil Conservation Service of the U.S. Department of Agriculture, the Special Area Management Plan of the Office of Coastal Zone Management of the National Oceanic and Atmospheric Administration (if applicable), National and State parks, forests, etc., and any local jurisdiction zoned land uses that may be impacted by the SSC.

Information Needed

* (i). A discussion of existing and proposed uses of the lands within and adjacent to the SSC project.

(ii). Aerial photographs, maps, drawings, or other graphics sufficient to show the location, extent, and nature of the land uses referred to under (i) above.

(iii). Identification of lands that could be used for disposal of excavated spoils.

2. Surface Water

The construction and operation of the SSC will impact the surface-water hydrology of the proposed site, including water quantity, water quality, flooding and drainage, and low flow/drought.

a. Quantity

It is important to identify any drainage basins and major surface-water features such as streams, lakes, reservoirs and other water courses that may be in the region of a proposed SSC site. Water flow and volume information will be required in sufficient detail to determine normal and seasonal variability making use of historical records of flow and volume.

Information Needed

* (i). A map delineating major drainage basins and identifying major surface-water features.

(ii). The baseline and seasonal variations in quantity for the surface waters.

b. Quality

The surface waters identified above will have seasonal variations of quality. Water quality may be temporarily affected by the construction and operation of SSC. Water quality information should include: nutrients, pH, total residue, nonfiltrable residues, dissolved oxygen, total alkalinity, significant heavy metals, temperature, and turbidity.

Information Needed

(i). The baseline and seasonal variations in quality for the surface waters identified.

(ii). An estimate of the effect on surface-water quality of the construction and operation of the SSC.

c. Flooding/Drainage

The proposed construction or operation of the SSC may be affected by extreme flows in the surface waters, as well as other drainage difficulties such as poorly draining soils. Useful information would contain available flood mapping (i.e., HUD or COE Flood Plain maps), historical flooding information (profiles or spot elevations), and would identify special drainage difficulties due to surface or subsurface conditions.

Information Needed

(i). Identification on maps of the extent of flood areas and corresponding flood frequency.

(ii). The pattern of historical and anticipated flooding and drainage conditions for the surface waters within the SSC project area.

(iii). Special drainage difficulties that might be anticipated in the proposed project area.

d. Low Flow/Drought

A drought over a sustained period of time could be a serious problem for the SSC. Since water will be needed for a variety of uses, it is not practicable to define a drought specific limitation for the project at this time.

Information Needed

(i). Recorded drought or low-stream histories for surface waters in the region of the proposed SSC site, including the most severe dry period and low stream flows on record.

3. Ecology

The construction and operation of the proposed SSC project may impact the fish, wildlife, and botanical resources in the project area. The ecological resources in the area must be evaluated under each of these categories.

a. Fish and Wildlife

Fish and wildlife may be impacted by the proposed SSC project. Some species may be considered important because of their commercial or recreational value. Other fish or wildlife in the area may be proposed for listing or are listed as threatened or endangered by the U.S. Department of the Interior or Department of Commerce.

Information Needed

(i). Description of the significant fish and wildlife resources in the vicinity of the proposed SSC project area and their locations.

* (ii). The habitats of threatened or endangered species and any species in the project area that receive any other type of special protection.

(iii). A map showing the distribution of the fish and wildlife discussed under items (i) and (ii) above.

b. Vegetation

SSC construction and operation might impact the botanical resources of a proposed site by permanently altering the terrain, or by excavation and heavy traffic during construction. Of particular concern are vegetation types and plant species proposed or listed as threatened or endangered by the U.S. Department of Interior and Department of Commerce.

Information Needed

(i). Description of the significant botanical resources in the proposed SSC project area.

* (ii). The habitats of threatened or endangered species.

(iii). A map showing the distribution of vegetation types discussed under items (i) and (ii) above.

4. Air Quality

The air quality at the proposed SSC site will not be affected by the project during operation; however some dust and noise problems will be encountered during construction. To evaluate these, a summary will be needed of meteorological conditions affecting the dispersion of air pollutants and current and historical data on ambient air quality. The attainment status of the air-quality control regions containing the site is relevant to any evaluation.

Information Needed

(i). Data on the existing air quality, and the air-quality limitations for the proposed SSC site.

(ii). Anticipated cost of mitigation required in non-attainment areas.

(iii). Factors affecting dust generation including soil types and local conditions.

5. Background Radiation

The issues of radiation and radioactivation will be addressed by the SSC staff. Therefore, baseline information on the existing background radioactivity of the soil and water in the area of the proposed site is necessary.

Information Needed

(i). Available background data pertaining to soil and ground-water radioactivity levels in the region of the proposed site.

(ii). Information about local dose rates due to natural background radiation.

6. Historical and Archaeological Resources

Historical and archaeological resources are a national trust. Information should be provided to identify historic or archaeological resources within or near any proposed project area; the results of any surveys, inventories, and subsurface testing that may have been performed by local state and Federal agencies; places that are on the National Register of Historic Places; and other such information that is available from the state historic preservation officer or similar state official.

Information Needed

(i). Description of the historical and archaeological resources in the proposed SSC project area.

(ii). Discussion of any potential effects on historical and archaeological resources that might result from siting, constructing, or operating the SSC in this area.

7. Preliminary Environmental Evaluation

A preliminary evaluation should be made of the possible environmental impacts associated with the proposed construction and operation of the SSC project in the proposed area. The evaluation should specifically address the environmental characteristics covered above.

Information Needed

(i). A preliminary environmental evaluation of each site including a discussion of mitigation or protection measures.

This environmental evaluation will be used to help fulfill the requirements for NEPA compliance.

* (ii). Identification of major impacts that would require special attention or that could limit the use of the proposed site.

(iii). The possible impacts of the proposed SSC project on other environmental characteristics such as socio-economic resources, recreational resources, and aesthetic or visual resources.

C. GEOLOGY AND TUNNELING

Surface and subsurface conditions will directly affect the design and construction of nearly all structures of the facility. The largest single structural component, the collider ring, will be constructed underground. Ground conditions can materially affect the cost and schedule of its construction, and, possibly, the feasibility of construction.

1. Topography

Topography is significant because it is the primary determinant of the variation in depth of cover above the collider tunnel. Since depth has an impact on the probable types of tunneling, access shafts, and the design of experimental areas, topographic conditions must be carefully considered.

Information Needed

* (i). An illustration of the proposed location and profile of the SSC showing the maximum and minimum depths of cover for the collider, injector, and experimental areas based on topographic maps (either the same USGS maps furnished under Section A or other more detailed mapping).

2. Geology

The geologic setting defines, to a large measure, the principal geotechnical characteristics of a site. For construction purposes, relatively uniform geologic characteristics are preferred. Structural features, such as faults or shear zones, or buried valleys in the bedrock, may pose local construction difficulties, especially if associated with large quantities of ground water. Soft soil conditions such as certain clay deposits will require special, and often costly, tunneling or deep excavation methods and may pose foundation problems for surface facilities.

Information Needed

* (i). Geologic maps of the site area that define major geologic units to the depth of interest, together with an engineering description of these units.

(ii). Identification of significant structural geological features that may pose construction problems.

(iii). Locations and extent of soft clay, unconsolidated sand, or other soil conditions that may pose tunneling, excavation, or foundation problems.

3. Geohydrology

Ground water may pose significant underground construction problems in pervious soils or when rock tunnels traverse pervious geologic structures and shear zones. As a practical matter, tunnel construction at depths greater than about 100 feet in unconsolidated granular soils containing ground water becomes very difficult. Pervious structural features in rock can usually be consolidated, but tunneling through a number of such features would be time consuming and costly. Excavation for cut-and-fill tunnels and shafts in water-bearing ground is also difficult and may require costly and time-consuming construction methods.

The chemical content of the ground water may have an effect on the choice of construction methods. Certain types of ground water could pose problems of dewatering and water disposal during construction. The corrosivity of the water and the geologic material may require special provisions in the selection of construction materials and corrosion protection.

Information Needed

* (i). Detailed characteristics of the overall geohydrological regime including ground water, and the interaction with surface streams and precipitation.

(ii). The depth to ground water and annual variations in ground water levels around the site.

(iii). Current and proposed ground-water use.

(iv). Identification of locations where underground construction may be impacted as a result of ground-water pressure or inflows, or by chemical constituents of the ground water, including alkalinity and salinity.

4. Seismicity

In a seismically active area special design provisions may be required.

Information Needed

* (i). A characterization of site seismicity, in terms of zone designation according to the Uniform Building Code. If in Zone 3 or 4, additional site-specific seismic data should be obtained.

(ii). An estimate of the site-specific maximum credible event.

(iii). Identification on the map of any faults in the site area that are known or suspected to have been active in the last 10,000 years.

5. Tunneling and Underground Construction

Reference has been made in previous sections to the topography, the geologic setting, and the geohydrology. The impact of these features on the feasibility, cost, and schedule of construction cannot be assessed without information about the soil and rock along the proposed alignment of the underground structure.

Information Needed

(i). Geologic information indicative of that along possible SSC alignments, showing relevant geologic units, structural features and topography, aquifers, and ground-water table.

(ii). An engineering description of relevant soil and rock units, including a description of potential local construction difficulties associated with geologic structures and anomalies based upon existing data.

* (iii). A recommended construction approach for the conditions present on each proposed site. Any features that require novel or unusual methods should be indicated.

D. COMMUNITY RESOURCES

Beyond the technical necessities, such as land availability and suitable geological conditions, are a number of other desirable regional characteristics, including the availability of skilled labor, housing and other community services, industrial resources, educational and research facilities, recreation, and cultural resources in the vicinity of the proposed site.

1. Human Resources

In addition to scientists, the accelerator laboratory will require mechanical, electrical, and civil engineers, architects, programmers, machinists, technicians for accelerator operation and experimental setup, computer operators, designers, and other similarly skilled and semi-skilled personnel. A region should have available a labor pool that permits recruitment and retention of qualified personnel for construction and operation of the SSC.

Information Needed

* (i). A description of the geographic distribution of population in relation to the proposed site.

(ii). A description of the labor pool and prevailing wage rates in the region.

(iii). Regional employment trends by industry and occupation, e.g., growth in high-technology employment in the state.

(iv). A demographic profile of the existing and projected population in the region.

2. Housing and Community Services

The SSC is a complicated device that will operate 24 hours a day, so personnel must live relatively close to the site. It should be located near a community or communities that can provide and/or develop housing and other necessary services for the 3000 full-time and visiting scientists and staff. The laboratory will be an Equal Opportunity employer, and this practice must be reflected in housing availability.

a. Housing

Housing needs typically include:

Single-family homes for sale or rent in nearby communitie (single-family detached units, townhouses and condominiums).

Single-family homes or apartments available for rent for visitor and staff.

Motels and hotels for short-term visitors.

Information Needed

* (i). Characterization of housing available or planned i the region.

(ii). Description of housing distribution, typical purcha prices and rents for the housing types mentioned above.

(iii). Description of the potential for future housing su ply.

b. Community Services

Community facilities and services including recreational, medica and public services facilities are needed in the region of the SSC.

Information Needed

(i). Identification of medical centers, hospitals, emergency services including the number of beds, size staff, and other relevant information.

(ii). Information on the availability and responsive ca bility of police and fire and rescue services in the nea communities.

(iii). A description of community recreational and op space facilities including parks, centers for spectator participatory sports, and other areas for recreation.

3. Accessibility

Adequate transportation facilities should be available to the posed site to permit convenient and efficient access for the traffi personnel, materials, and equipment required in the construction operation of the SSC. The site should be served by a system of In state and state highways, and local roads of sufficient capacity accommodate the additional traffic expected to be generated by Regional public transportation should be available to serve the SSC campus. Highway travel between SSC and a major urban center should be convenient.

a. Airports

There should be a major airport convenient to the SSC because the research to be conducted there will attract a steady flow of scientists and other visitors from around the nation and the world.

Information Needed

(i). Information on size, location, and service characteristics of local, regional and/or international airport(s) in the vicinity of SSC.

(ii). The number and size of air carriers, number of scheduled daily arrivals and departures, and the destinations directly served.

(iii). Operational limitations, such as the average number of days per year the airport is closed because of bad weather.

b. Highways, Streets, and Roads

Highways, streets, and the road network in the vicinity of the proposed site are important to the configuration of the SSC. Access roads and highways must be able to accommodate long-bed (HS-20-44 design) vehicles as specified by the American Association of State Highway and Transportation Officials (AASHTO).

Information Needed

(i). The present characteristics of the major routes serving the site, including vehicle restrictions (length, weight, height), route capacity (vehicles per hour), and peak traffic rates.

(ii). Identification of any improvements to the existing road and highway network needed to support the construction and operation of the SSC at the proposed site.

(iii). Statements on maintenance responsibility for access roads and highways serving the site.

c. Public Transportation

Once in operation, the SSC will attract a regular flow of visiting scientists and other visitors who because of their non-resident status will depend on public transportation to and from the site. Availability of various types of transport, such as intercity rail and/or bus, regional bus, vanpool, limousine, taxi, and rental cars, would be desirable.

Information Needed

(i). A description of available public transportation systems and services in the vicinity of the proposed site including airport access.

(ii). Discussion of the improvements to the public transportation systems and services required to adequately serve the SSC.

d. Railroads and Waterborne Transportation

Availability of rail transportation in the vicinity of the site is desirable. If the proposed site is near a navigable waterway, it might be advantageous alternatively to transport certain bulky equipment and/or materials to the site by water.

Information Needed

(i). The type and extent of rail service available in the vicinity of the SSC site.

(ii). Service characteristics, available connections to Class 1 railroad mainlines, and existing load limitations where known.

(iii). Assessment of the capability of the available rail system to handle special equipment and supplies needed for the construction and operation of the SSC.

(iv). Description of any waterborne transportation facilities and services available to the proposed site.

4. Construction Resources

The SSC will require large amounts of conventional construction materials and equipment. Sources of supply will be required for these critically needed items:

Cement and aggregate material
Steel fabrication services
Electrical power equipment
Mechanical systems equipment
Construction equipment maintenance and repair

Information Needed

(i). Description of sources of construction materials and equipment with indication of their adequacy.

5. Industrial Resources

A large accelerator such as SSC will require many specialized and conventional industrial services. It would be desirable for as many of these as possible to be available in the immediate area. Some of the most important of these services are:

Sources of compressed and liquefied gasses (He, N_2, O_2)

Sources of industrial solvents

Electrical and electronic fabricators

Heavy-equipment maintenance facilities (for rewinding generators turning shafts, etc.)

Specialized heavy-equipment rental

Maintenance services— vehicles, computers, office machines

Vendors' regional warehouses with fast service on parts

Information Needed

• (i). Discussion of the accessibility of the proposed site to an industrial base to support the construction and operation of the proposed SSC.

(ii). Characterization (capacity, distance) of the nearest source capable of supplying liquid nitrogen (LN), and purified helium.

6. Educational and Cultural Resources

Proximity of the site to universities, research centers, and other educational institutions is desirable. Nearby campuses could be valuable sources of professional personnel for the SSC as well as offering continuing education and library access opportunities to the staff.

Community colleges and technical schools are other valuable resources that would offer continuing education opportunities for the SSC staff and could attract and develop technically skilled labor for the SSC operation.

The quality of elementary and secondary education is often a decisive factor for families considering relocation. Quality education could help attract professional personnel needed for the SSC.

A consideration in determining the attractiveness of a site and its potential for retaining SSC staff is the proximity and extent of cultural resources.

Information Needed

• (i). Identification of all higher educational and research institutions in the vicinity of the proposed SSC site.

(ii). Brief descriptions of the enrollment, curricula emphases, faculty size, and other relevant information for the institutions identified above.

• (iii). Description of elementary and secondary educational facilities for children of permanent staff members and long-term visitors.

(iv). The numbers and capacities of public and private schools, current enrollment levels, student/teacher ratios, SAT or ACT score averages for the last 5 years, evidence of community attitude about education, expenditures per pupil for the last 5 years, fiscal health, and other indications of educational quality are some of the needed information.

(v). Description of libraries, museums, performing arts centers, places of worship, and cultural resources in the vicinity of the proposed SSC site.

7. Community Support and Assessment

Community support will play an important role in the ultimate success of the SSC. It will actively seek the support of the surrounding communities by establishing a good-neighbor policy. It is important to determine at an early stage what community support exists and how strong any opposition might be to siting the SSC in a region.

Information Needed

* (i). Discussion of the community support for the proposed SSC that exists and its likelihood of growth.

(ii). A characterization of any opposition known to exist, or anticipated, in siting the SSC as proposed.

E. UTILITIES

As discussed in Part III, utility supply availability, capacities, and costs are important considerations for the SSC. Sufficient supplies of water and electric power are particularly crucial. Electrical power requirements will depend significantly on the cooling systems designs finally selected. Design of the industrial cooling system, will be largely influenced by climatic conditions, particularly wet and dry bulb temperatures, wind, and the availability and quality of cooling water sources.

Availability of industrial cooling water is a major requirement for the proposed SSC. Most of the cooling water will be used in the collider ring, and to a lesser extent in the injector and central laboratory. As described in Part III, limited availability of cooling water would increase the power demand significantly, as much as 25%. Accurate information relative to the availability of industrial cooling water is needed both for summer and winter months. Available sources, water quantity and distribution, quality and utilization of return flows are the main issues to be considered.

If improvements to the utility systems are required to meet the SSC's requirements, a timely commitment on the part of the proposer to make these improvements would be essential.

A complete system of telecommunications will be required to support the operation of the SSC. An adequately sized regional communications network will be required. Local and intra-facility communications links will also be required.

1. Power

Primary power could typically be supplied to the SSC site at transmission voltage in the range of 230 kV to 500 kV. Separate feeds, connected to different points on the grid, will be required to provide adequate reliability. Generating capacity and power grid stiffness are of concern. For purposes of estimating power requirements and rates, one can assume the following operating cycle for the major machine components, including particularly the refrigerator/compressor equipment:

Time	Mode of Operation	Ave. Power Requirement
2/3 year	Full	100%
1/3 year	Stand-by	40%

Information Needed

• (i). A description of the electric power generating and transmission grid system, including location of generating stations, type of primary energy sources, and generating capacities.

(ii). A map of the transmission network showing lines, voltages, and capacities, including the location of switching stations and substations.

(iii). An analysis of the power system stability at the proposed SSC site, including both steady-state and transient stability evaluations.

(iv). Experience with the reliability of electrical power service.

(v). Utility rate schedules that include energy and demand charges for an industrial load represented by the SSC. Indicate any preferential rate concessions for the SSC and their duration.

(vi). Projection of future power demand growth and future costs in the region including an evaluation of how the SSC would impact this projection.

2. Fuel

Heating required for SSC is expected to vary from 55,000 MBtu/hr for a desirable climate representing 900 degree-days (base 65°F) for a winter month, to 73,000 MBtu/hr for a colder climate with a 1200 degree-day winter month. Information on fuel availability, reliability of supply, and cost for all fuel types available to the site, including as applicable natural gas, coal, oil, solar, and geothermal is desirable.

Information Needed

• (i). Description of how the fuel heating/cooling requirements for the SSC could be met.

(ii). The cost factors in dollars per million Btu per hour ($/MBtu/hr).

3. Water

Information on sources of usable water, means of conveyance, treatment requirements and cost is relevant to utility considerations. Other aspects, such as availability of water rights or environmental impacts are dealt with in other sections.

a. Industrial Cooling

To meet the needs of the SSC systems it will be necessary to consider the available sources of water, water quantity and quality, seasonal variations, and flow rates. Sources may include surface water, ground water, spring water or any other locally available suitable source. For underground water sources, location of wells, nature of aquifers and the ground-water potential of the underground basin will be relevant. Cooling water should comply with applicable standards.

Information Needed

* (i). Itemization of the available sources of water proposed for use as industrial cooling water in the format shown in Table A.

(ii). The estimated cost of industrial cooling water delivered to the site ($ per million gallons) based on the resources listed in Table A.

(iii). Description of the physical and chemical properties of the water available for use as industrial cooling water and any treatment that may be required.

TABLE A

SOURCES OF WATER AND FLOW RATES
(MILLION OF GALLONS PER DAY)

Name of Source	Distance from Site (Miles)	Surface Water Flow Rate		Spring Water Flow Rate		Other Sources Flow Rate	
		S	W	S	W	S	W
1.							
2.							
etc.							

S = Summer; W = Winter

b. Potable

The quality of water available at the site will play an important role in determining its suitability as potable water. The quality of potable water must comply with the National Interim Primary Drinking Water Regulations and the state's drinking water quality standards.

Information Needed

(i). Itemization of the sources of water available for use as potable water. (Refer to Table A.)

(ii). Estimates of the present and projected cost of potable water delivered to the site ($ per million gallons).

(iii). Discussion of whether the quantity of water available, particularly during periods of low flow, will be sufficient to support the SSC population.

(iv). The expected physical, organic, and biological properties and chemical composition of the water after treatment.

4. Waste Disposal

SSC facilities will generate both liquid and solid wastes; both must be disposed of properly. Information on the availability, capacity, and proximity of environmentally acceptable disposal sites or other means of solid waste disposal should be obtained.

a. Sewage Disposal

It is anticipated that the sanitary network for the campus, including the industrial and injector areas will be served by a pipe collection system discharging to a centralized sewage treatment plant or to an existing sewage treatment plant, if such a facility is available in the vicinity.

Information Needed

(i). A description of the available treatment facilities that might be used to serve SSC, including proximity to the site and cost of connection.

b. Solid Waste Disposal

The quantity of solid waste to be generated at the SSC facility is expected to be about 30,000 cubic yards per year. The SSC may elect to dispose of this solid waste in an on-site landfill or choose other options such as incineration or off-site disposal, including recycling.

Information Needed

(i). Identification and description of what type of solid waste disposal resources are available for SSC's use.

(ii). Identification of any existing or proposed landfill, incineration or recycling plant near the proposed site.

5. Telecommunications

A high-speed digital telecommunications system will be required to support the operation of the SSC. It is anticipated that the SSC facility will include a Private Automatic Branch Exchange (PABX) with an estimated capacity of 4000 lines and 200 trunks.

Information Needed

(i). A description of the extent and proximity of existing switching stations, including the number of trunks available.

(ii). An estimate of the anticipated costs, including connection and usage fees, for the required external communications system.

(iii). A forecast of anticipated growth of the regional system demand, the impact of the SSC facility on the forecast, and the planned activity to meet the forecasted demand.

F. MAN-MADE DISTURBANCES

1. Vibration

As noted in Part III, the particle beams in the SSC have cross-sections of less than one thousandths of an inch, but must be held in collision for many hours. For this reason, the SSC is very sensitive to vibrations that would displace the beams from one another. These vibrations could be occasional, as from blasting operations, or continual, as from heavy trucks, rail traffic, or operation of heavy machinery.

Information Needed

* (i). An identification of sources of vibration such as major highways, railroads, quarries, or heavy machinery operations present in the area, and an estimate of their intensity.

2. Noise

It will be necessary to evaluate the effect of noise in and adjacent to a proposed site. Information on principal sources and levels of noise in a proposed project area will be needed.

Information Needed

* (i). Identification of the principal sources and levels of background noise in and around the proposed SSC project area.

(ii). Noise contours of areas in and adjacent to the proposed site, if available.

(iii). Identification of noise-sensitive land uses located in any project area.

. CLIMATE

The schedule and cost of construction, as well as the long-term operational cost of the laboratory, will be significantly influenced by local climatic conditions. Extreme conditions of temperature, humidity, wind, rain and related flooding, snow and ice, fog, and the duration of such extremes are of practical concern. Adverse conditions would directly affect design and construction activities and also influence the long-term operating efficiency and costs of the SSC.

The kinds of information needed on climatic conditions (averages, extremes, durations, and frequencies) are delineated below.

1. Temperature and Humidity

Table B lists recommended categories of information on temperature and humidity. Sources of information should be identified with respect to the location of weather reporting stations and periods of record along with other qualifying information.

Information Needed

- (i). Temperature and humidity data. (Refer to Table B.)

  (ii). The average winter frost penetration. (Refer to Table B.)

TABLE B
AVERAGE CLIMATIC CONDITIONS BY MONTHS

Month	Average Low Temp. (F^{O})	Average High Temp. (F^{O})	Average Relative Humidity (%)	Average deg-days (base 65°F)	Average Frost Penetration (in.)	Precip-itation (in.)
Jan. through Dec.						

2. Precipitation

The amount of precipitation in solid form (snow, ice, hail, sleet) or liquid (rain) that falls on a proposed SSC project area will be important during both construction and operating phases.

Information Needed

- (i). The average monthly precipitation. (Refer to Table B.)

  (ii). The frequency and duration of precipitation extremes and depths of snowfall.

3. Wind

Wind transports dust, silt, and sand and is also a structural concern because of possible extreme wind forces.

Information Needed

(i). The prevailing wind direction and speed. (A wind rose, if available, should be obtained.)

(ii). Information on extreme wind conditions (magnitude, frequency and duration).

4. Regional Storms

Severe weather conditions will affect the time schedule and cost of construction as well as the operation of the SSC project. The types of storms that need to be considered include large air-mass movements, fronts, squall lines, hurricanes, tornados and convective weather such as thunderstorms.

Information Needed

(i). Description of the regional storm characteristics including types, frequency of occurrence, and severity.

5. Insolation

The amount of sunshine, i.e., the intensity of solar radiation and the number of clear days per month, that is available for heating and cooling of the SSC facilities is of interest.

Information Needed

(i). The daily average solar irradiation in Btu/sq ft for summer and winter months.

(ii). The average number of clear days per month.

H. COST AND SCHEDULE

The foregoing sections have itemized specific information bearing on various cost and schedule factors for the SSC.

1. Cost Factor

In the construction area the information would yield desirable data on costs for land, water supply, electric power connections, roads, and other facilities. For operation the cost of electrical power, fuel, transportation, maintenance, etc., must be considered both year by year and over the lifetime of the facility.

Information Needed

(i). Summary of cost information relevant to the siting, construction, and operation of the SSC.

(ii). Assistance and concessions that might be offered with respect to locating the SSC in the proposed region.

APPENDIX 15

SSC-SR-1011

INTERIM REPORT

SSC CENTRAL DESIGN GROUP*

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* OPERATED BY UNIVERSITIES RESEARCH ASSOCIATION FOR THE DEPARTMENT OF ENERGY.

SSC INTERIM REPORT - June 1985

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PREFACE

This Interim Report summarizes the research and development activities of the Superconducting Super Collider project carried out from the completion of the Reference Designs Study (May 1984) to June 1985. It was prepared by the SSC Central Design Group in draft form on the occasion of the DOE Annual Review, June 19-21, 1985. This final version contains essentially the same material as the draft, but in a different format.

Now largely organized by CDG Divisions, the bulk of each chapter documents the progress and accomplishments to date, while the final section(s) describe plans for future work. Chapter 1, Introduction, provides a basic brief description of the SSC, its physics justification, its origins, and the R&D organization set up to carry out the work. Chapter 2 gives a summary of the main results of the R&D program, the tasks assigned to the four magnet R&D centers, and an overview of the future plans. The reader wishing a quick look at the SSC Phase I effort can skim Chapter 1 and read Chapter 2.

Subsequent chapters discuss in more detail the activities on accelerator physics, accelerator systems, magnets and cryostats, injector, detector R&D, conventional facilities, and project planning and management. The magnet chapter (5) documents in text and photographs the impressive progress in successful construction of many model magnets, the development of cryostats with low heat leaks, and the improvement in current-carrying capacity of superconducting strand. Chapter 9 contains the budgets and schedules of the CDG Divisions, the overall R&D program, including the laboratories, and also preliminary projections for construction.

Appendices provide information on the various panels, task forces and workshops held by the CDG in FY 1985, a bibliography of CDG and Laboratory reports on SSC and SSC-related work, and on private industrial involvement in the project.

The early version of the report was prepared by the CDG staff, J.R. Sanford responsible. J.D. Jackson edited the final version.

M. Tigner
Director

CHAPTER 1. INTRODUCTION

This is a report of progress since the completion of the Reference Designs Study (RDS) of May 1984.[1] Since that time the major focus of activity has been on the most costly systems identified in the RDS, the bending magnet and tunnel systems. Cost analyses, engineering studies, and component R&D have continued. Work to date has supported the RDS conclusions that the SSC is technically feasible and that the accelerator facility itself (exclusive of land acquisition, R&D and pre-operating costs, and the initial complement of detectors) can be built for less than 3 billion dollars (1984).

This chapter presents a brief description of the project and its scientific maturation and history, as well as the objectives for Phase I and the organization created to carry it out.

1.1 SSC Facility Description

The SSC facility is a unique high energy physics laboratory whose major research instrument is a high-luminosity multi-TeV hadron collider. The collider will provide effective access to particle-particle collisional energies at least an order of magnitude greater than are available at existing facilities. The major design objectives for the collider are given in Table 1-1.

Table 1-1. Primary SSC Design Objectives.

Maximum proton beam energy (TeV/beam)	20
Maximum luminosity ($cm^{-2}s^{-1}$)	10^{33}
Number of interaction regions	6

Different magnetic field strengths for bending the proton beams are being explored in the Phase I R&D program. The low field (3T) would result in a main ring of magnets approximately 100 miles in circumference, while the high field (6T) would yield a ring circumference of roughly 60 miles.

The complete SSC facility is comprised of the 20 TeV per beam collider, an injector complex, interaction halls and associated support buildings, and a central complex of office and laboratory buildings. The injector complex consists of a cascade of accelerators that successively boost the particles to higher and higher energies for ultimate injection into the main ring, where they receive their final acceleration to 20 TeV. The interaction halls (underground, with extensions on the surface) are located at the interaction regions where the counter-rotating beams are made to collide. Staging halls are adjacent to the interaction areas for convenient assembly and testing of detectors before installation at the interaction point. The central complex provides the control center of accelerator operations, laboratory and office space for scientists, support services, and administration.

1.2 Scientific Motivation

Since the 1930's the development of accelerators has largely set the pace of discovery in particle physics, specially since the 1940's and 1950's with the development of powerful synchrocyclotrons and synchrotrons. These post-war machines were able to convert energy into new forms of matter, hitherto seen only in very low abundance in the cosmic rays. The controlled and flexible conditions of the laboratory provided the basis for rapid and impressive progress far beyond the cosmic rays, from Lawrence's first cyclotron in 1931 (5 inches in diameter and 100 keV in proton energy) to Fermilab's Tevatron (1-1/4 miles in diameter and 900 GeV in proton energy).

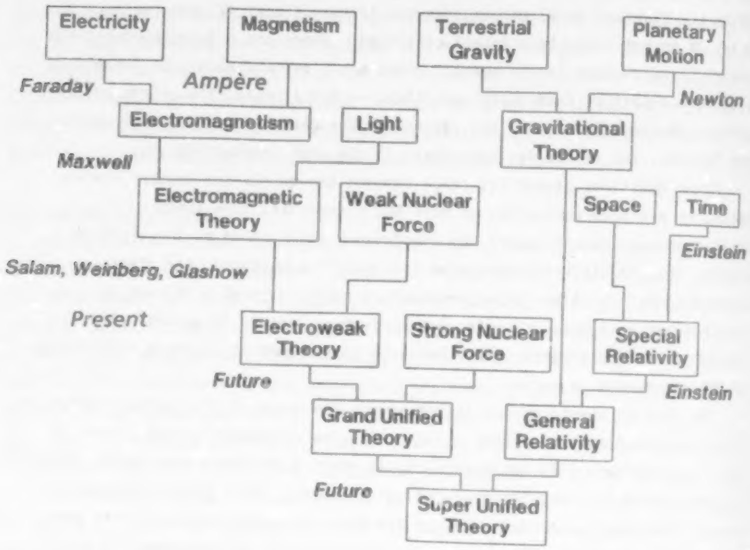
The inexorable upward thrust in energy is a consequence of two basic laws of nature. The first is that to "see" an object of a certain size it is necessary to use radiation (either sound or light or particles) of a wavelength smaller than the object to be studied. If we wish to probe deeper and deeper into the heart of matter, we must use shorter and shorter wavelengths. The second natural law is that the wavelength of a particle or of light is inversely proportional to its energy (strictly speaking to its momentum, but at high energies the difference is negligible). Shorter and shorter wavelengths therefore require higher and higher energies. To begin to probe the nucleus requires protons of several MeV; to probe the proton itself, several GeV; and to probe deep inside the proton and explore its basic constituents requires energies of many TeV.

The physics need for the SSC has been discussed in a number of places.[2-8] Only a brief sketch is presented here. The tremendous progress of the last 25 years, in experimental discovery and in theoretical synthesis has given physicists a remarkably successful description of the fundamental laws of nature, called the Standard Model. It is based on quarks and leptons as the elementary building blocks of all matter, interacting by forces carried by gauge bosons (the photon of electromagnetism being the most familiar). While the Standard Model encompasses and relates almost all observations to date, it is not complete and self-contained. There are a large number (~20) empirical parameters in the model. These are a reflection of its failure to explain a number of fundamental questions -- for example, the origin and pattern of particle masses, the reason for the observed groupings of quarks and leptons, the reason for handedness in the weak interactions.

Other questions beyond its reach abound: Are quarks and leptons really basic, or are they composites of more basic entities? Are there unifications of forces beyond the electroweak unification of the Standard Model? Can gravity be incorporated into particle physics? Are other, grander symmetries like "supersymmetry", a unification of particles of integral and half-integral spin, realized approximately in nature? Figure 1-1 indicates the progress since Newton's time toward an ultimate unification of all the forces of nature.

The list of questions and issues beyond the scope of the Standard Model is long, but its domain of proven validity is also extensive -- sufficient, in fact, to provide a firm basis for judging where experiments must go in order to answer many of the pressing questions of today. Very general arguments lead to the conclusion that study of the mass or energy range of 1 TeV and beyond must reveal new phenomena. The nature of the new phenomena is not known -- different theoretical extensions of the Standard Model make different predictions -- but behavior beyond or different from what is known at 100 GeV and below must occur.

For example, the so-called Higgs particle, seemingly necessary for the spontaneously broken symmetry of electroweak dynamics, may be a low-energy approximation to a rich and complex dynamics of bound states of a type of super-quark and super-strong force. Experiments that probe masses of 1 TeV should reveal these new systems. On the other hand, perhaps the Higgs particle is a basic constituent. If its mass is less than 1 TeV, the strong and electroweak dynamics will continue to be separately recognizable in the 1 TeV energy range and well beyond. But if the Higgs mass is large compared to 1 TeV, all the forces must become strong, and complex new phenomena, not



Unification of the forces of nature

Electricity
Magnetism
Terrestrial Gravity
Planetary Motion
Faraday
Ampère
Newton
Electromagnetism
Light
Gravitational Theory
Maxwell
Electromagnetic Theory
Weak Nuclear Force
Space
Time
Einstein
Salam, Weinberg, Glashow
Present
Electroweak Theory
Strong Nuclear Force
Special Relativity
Future
Einstein
Grand Unified Theory
General Relativity
Future
Super Unified Theory

Fig. 1-1. History of unification of our understanding of the basic forces and speculation as to its possible future course. At present, the Electroweak Theory and the Strong Nuclear Force (called QCD) form the basis of the Standard Model.

known today, will result. In any of these eventualities (and others not described), something new must be seen as the 1 TeV mass domain is explored.

The need for multi-TeV hadron beams to explore masses of 1-4 TeV stems from the compositeness of hadrons. The proton and other hadrons consist of quarks and gluons sharing the energy of motion. When hadrons collide at very high energies, the hard collisions that correspond to distances much smaller than the size of a hadron occur between constituents, rather than between the hadrons as a whole. Since the constituents each carry less than the total energy of the hadron, the energy available for the hard collision (and potentially convertible into mass) is generally much less than twice the beam energy of the hadrons. To study the short distances corresponding to masses from 1 to 4 TeV requires proton beam energies up to 20 TeV.[9]

The desirability of a next step in accelerator energy toward 20 TeV/beam is one thing, its realization another. Fortunately, the 20-year program of development of superconducting accelerator magnet technology provides a proven base on which to build. There now exist sophisticated industrial techniques for the production of highly stable, multifilament, superconducting strand (NbTi in a copper matrix) of very high current-carrying capacity and its fabrication into magnet cable of carefully controlled dimensions. Fermilab's Tevatron, with its one thousand large superconducting magnets (and another thousand smaller ones), is an "existence proof" of this still developing technology. One can therefore conceive of constructing larger accelerators based on this technology, exploiting the higher magnetic fields without the inordinately high electric power costs associated with conventional copper and iron magnets. Superconductivity is the key to the feasibility of the SSC.

1.3 Recent Chronology

The concept of a multi-TeV accelerator was first discussed in public about ten years ago. Two workshops sponsored by the International Committee on Future Accelerators (ICFA), one at Fermilab in 1978 and one at CERN in 1979, discussed various possibilities for very high energy machines, including proton-proton colliders in the 20 TeV per beam range. The SSC itself can be said to have had its origins in the 1982 Snowmass Summer Study, sponsored by the Division of Particles and Fields of the American Physical Society, and the recommendation a year later by the High Energy Physics Advisory Panel (HEPAP) to the Department of Energy (DOE) for the construction of a multi-TeV, high-luminosity hadron collider at the earliest possible date. The recent chronology is summarized below.

Summer 1982: A Summer Study of the American Physical Society's Division of Particles and Fields was held at Snowmass, Colorado. An in-depth examination of the idea of a 20-TeV/beam proton-proton collider resulted from this meeting. Strong and widespread support for the physics goals of such a collider emerged.

February 1983: A week-long workshop was held at the Lawrence Berkeley Laboratory (LBL) to consider detector problems for high-energy, high-luminosity hadron-hadron colliders.

March 1983: A workshop was held at Cornell University to consider technical and cost questions associated with construction of a multi-TeV hadron-hadron collider.

July 1983: A subpanel of the High Energy Physics Advisory Panel (HEPAP), convened early in 1983 to consider future high energy facilities in the United States, recommended immediate initiation of a project aimed at the construction of a new high-energy, high-luminosity, hadron collider. This recommendation, "unanimously . . .and enthusiastically endorsed by HEPAP with the highest priority" for high energy physics, was transmitted to DOE.

Fall 1983: DOE initiated preliminary R&D for the SSC. Hearings were held before the House Science and Technology Committee concerning redirection of resources toward the SSC R&D.

December 1983: The Reference Designs Study was chartered by the directors of the U.S high-energy accelerator laboratories with the energy and luminosity goals defined.

March 1984: DOE assigned responsibility for oversight of the national SSC effort during the R&D preconstruction phase to the Universities Research Association (URA).

Spring 1984: The Reference Designs Study drew upon the expertise of about 150 accelerator physicists and engineers from across the nation. It concluded that a 20 TeV on 20 TeV proton-proton collider is technically feasible. The Study, also containing cost estimates, was extensively reviewed by DOE personnel and their consultants.

Summer 1984: A Summer Study of the American Physical Society's Division of Particles and Fields was held at Snowmass, Colorado, to examine the design and utilization of the SSC. It reaffirmed the parameters of Table 1-1 as important for the physics goals.

Summer 1984: Initiation of the Phase I R&D program for the SSC was approved by the Secretary of Energy. Extensive work on model magnets for the SSC was already underway at Brookhaven National Laboratory (BNL), Fermi National Accelerator Laboratory (FNAL), Lawrence Berkeley Laboratory (LBL), and the Texas Accelerator Center (TAC).

Fall 1984: The Central Design Group (CDG) was formed, with headquarters at LBL. The CDG has been charged with directing and coordinating the SSC R&D work.

1.4 Phase I Objectives

The purpose of the SSC Phase I effort is to carry out a comprehensive research and development program sufficient to determine a cost- and performance-optimized design, and to demonstrate that the key technical features of the accelerator-collider system are achievable within the estimated cost and schedule. The R&D effort is also to include assessment of the requirements of the initial complement of detectors for the projected SSC experimental physics research. Phase I is envisioned by the CDG to be of about three years' duration (FY 1985-1987).

In more detail, the overall objectives of Phase I are:

(a) To develop the performance specifications for the Superconducting Super Collider consistent with the recommendations of HEPAP and its 1983 Subpanel on New Facilities, with consideration of the results of subsequent pertinent studies and deliberations.

(b) To conduct SSC design and R&D activities, making use of the skills, experience, and facilities of National Laboratories, universities and the industrial sector.

(c) To select an optimum superconducting magnet design style for the SSC based upon technical, economic and operational criteria.

(d) To develop, as required for timely consideration in the FY88 budget process, an SSC Conceptual Design Report including costs, schedule, staffing plan, and other elements showing how the SSC can be realized in a practical, environmentally sensitive and safe manner.

(e) To evaluate site parameter requirements and to provide site information specification documents.

(f) To develop and demonstrate cost-effective techniques for fabrication of magnets.

(g) To conduct systems tests to evaluate performance and reliability of magnets and other components.

(h) To develop a site-specific plan and critical-path schedules following site selection.

(i) To develop a catalog of operating needs for the SSC, including utilities, cryogens, maintenance supplies, and manpower levels.

(j) To conduct or coordinate appropriate R&D activities for the development of advanced particle detectors.

1.5 Organization to Carry out Technical Objectives

In the spring of 1984 the Department of Energy selected the Universities Research Association, a consortium of 56 leading research universities, as to carry out Phase I of the SSC program. URA formed an SSC Board of Overseers to assure that the SSC efforts were carried out responsibly and independently of the URA-managed program at Fermilab. The Board of Overseers consists of academic, laboratory, and industrial scientists and engineers. Its current composition is James W. Cronin, University of Chicago; John M. Deutch, Massachusetts Institute of Technology; Harold P. Furth, Princeton University; John K. Hulm, Westinghouse Electric Corporation; Edward Knapp, Los Alamos National Laboratory; Boyce D. McDaniel, Cornell University, Chairman; George E. Pake, Xerox Corporation; Wolfgang K.H. Panofsky, Stanford University; Martin Perl, Stanford Linear Accelerator Center; Chris Quigg, Fermi National Accelerator Laboratory; Sam B. Treiman, Princeton University; George H. Trilling, Lawrence Berkeley Laboratory; and Steven Weinberg, University of Texas. The SSC Board of Overseers formed the SSC Central Design Group, appointed Dr. Maury Tigner of Cornell University as Director, and, upon his recommendation, approved the siting of the CDG at the LBL.

The relationship of the Central Design Group to URA, DOE, and the various R&D centers is indicated in Fig. 1-2. The CDG acts as the coordinating and management group for the SSC research and development being carried out at the

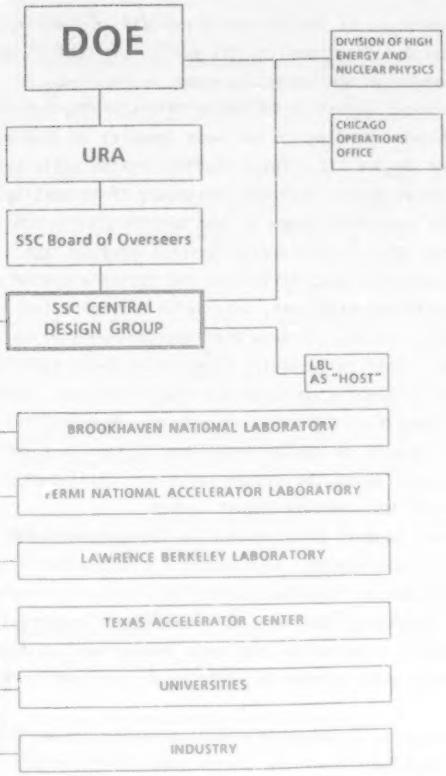

DOE
DIVISION OF HIGH ENERGY AND NUCLEAR PHYSICS
CHICAGO OPERATIONS OFFICE
URA
SSC Board of Overseers
SSC CENTRAL DESIGN GROUP
LBL AS "HOST"
BROOKHAVEN NATIONAL LABORATORY
FERMI NATIONAL ACCELERATOR LABORATORY
LAWRENCE BERKELEY LABORATORY
TEXAS ACCELERATOR CENTER
UNIVERSITIES
INDUSTRY

Figure 1-2. Organization chart showing the relationship of the Central Design Group to URA, DOE, and the various R&D centers. The DOE has additional direct lines of communication to the laboratories and other R&D centers.

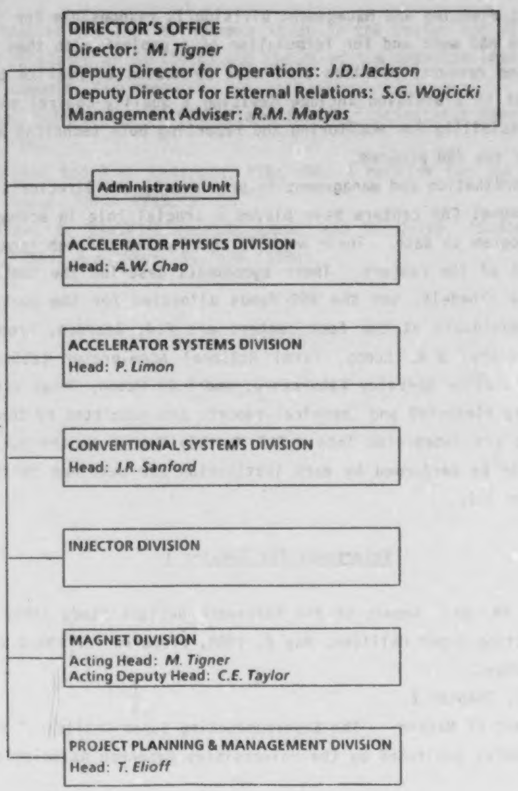
four magnet R&D centers, in the universities, and in industry, as well as within the CDG itself. To accomplish its goals, the Central Design Group is organized into a number of Divisions, as shown in Fig. 1-3.

The major technical objective of the Accelerator Physics Division is to obtain a detailed understanding of the beam dynamics of high-current stored beams as envisioned in the SSC. These studies provide basic specifications on such crucial issues as magnet aperture, necessary field quality, and alignment tolerances over the operating ranges of the various accelerator systems.

The R&D efforts of the Accelerator Systems Division are aimed at the development of a workable, cost-effective, and reliable system of accelerators consisting of magnets and cryostats, associated refrigeration, quench protection, power supplies, vacuum, rf acceleration, instrumentation and controls, abort systems, etc. This will require integration and reliability studies for development of system and system-interface specifications, system testing and specification of needs for component development. Modeling and prototyping of system components as well as system tests are an important part of Division activities. Principal among the system tests are those demonstrating integrated performance of the complete magnet system.

The Conventional Systems Division has as its technical R&D objectives to determine SSC site requirements, to prepare a site-parameter document that will be used by the DOE as technical advice in its site-selection process, and to explore ways to minimize the cost of conventional construction. To this end it will develop a site master plan and conventional system design that meets the scientific needs of the facility in a cost- and schedule-optimized fashion.

The Magnet Division is responsible for the selection of the basic magnet type and for the development of the design, specification and prototyping of that selected magnet. It directs and coordinates R&D work carried out at the magnet R&D centers (BNL, FNAL, LBL, TAC) and in the universities and industry. The main Phase I technical objective is to develop a magnet that meets the field-quality requirements of the SSC. Associated objectives are to optimize technical performance and reduce costs of the final design, to develop tooling and demonstrate manufacturability of SSC magnets in a reliable and cost-effective manner.


DIRECTOR'S OFFICE
Director: *M. Tigner*
Deputy Director for Operations: *J.D. Jackson*
Deputy Director for External Relations: *S.G. Wojcicki*
Management Adviser: *R.M. Matyas*
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ACCELERATOR SYSTEMS DIVISION
Head: *P. Limon*
CONVENTIONAL SYSTEMS DIVISION
Head: *J.R. Sanford*
INJECTOR DIVISION
MAGNET DIVISION
Acting Head: *M. Tigner*
Acting Deputy Head: *C.E. Taylor*
PROJECT PLANNING & MANAGEMENT DIVISION
Head: *T. Elioff*

Figure 1-3. SSC Central Design Group Organization

READEX FICHE

The Project Planning and Management Division is responsible for integrated planning of the R&D work and for formulation of a project plan that includes the schedule and resource profiles that will be needed to realize the SSC. Other duties of this Division include devising a quality-control plan, and also the responsibility for monitoring and reporting both technical and financial aspects of the R&D program.

Overall coordination and management is provided by the Director's Office.

The four magnet R&D centers have played a crucial role in accomplishing the Phase I program to date. Their work is coordinated through formal agreements with each of the centers. These agreements describe the tasks to be undertaken, the schedule, and the SSC funds allocated for the work. The responsible individuals at the four centers are P.J. Reardon, Brookhaven National Laboratory; R.A. Lundy, Fermi National Accelerator Laboratory; K.H. Berkner, Lawrence Berkeley Laboratory; and F.R. Huson, Texas Accelerator Center. Monthly financial and technical reports are submitted by these groups to the CDG and are integrated into a CDG Monthly Report to the DOE. The primary tasks to be performed by each institution are outlined in the next chapter (Section 2.2).

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CHAPTER 2. SUMMARY OF R&D PROGRAM

2.1 Results in FY 1985

The major milestones foreseen for Phase I are displayed in Table 2-1. The major focus of activity since completion of the RDS, as can be seen from the milestones, has been on the primary technical parameters of the SSC, i.e., the scientific specification, selection of the optimum superconducting magnet technology to be used for the collider accelerator, and continuing assessment of costs for constructing the SSC. In addition, attention has been given to describing the siting requirements for the facility. Planning for completion of Phase I work has also been a central effort.

The Summer Study on Design and Utilization of the SSC, conducted by the Division of Particles and Fields of the American Physical Society in June and July, 1984, reaffirmed the scientific design goals of 20 TeV per beam, high luminosity ($10^{33}cm^{-2}sec^{-1}$), and potential for six interaction regions.

Even prior to the formation of the CDG, considerable model work on superconducting magnets for SSC service had been carried out. At the beginning of FY 1985 an extensive review of the existing magnet program was carried out by a CDG-appointed panel of experts. This Technical Magnet Review Panel not only reviewed the status of the various magnet development efforts but also made suggestions on how the on-going program could be strengthened and refocused to permit an early selection of the Basic Magnet Type to be pushed forward to full-scale prototyping. A selection process has been devised which is based on the results of the engineering and modeling studies now proceeding, upon cost estimates for complete collider systems based on the five magnet types now under study, and upon system considerations having to do with commissioning and operation of the collider. The five magnet types under consideration* span the range of technical approaches that the previous

---

* The following nomenclature for the Basic Magnet Types is used:

Basic Magnet Type	Description
A	2-1, high field, cold iron
B	1-1, high field, warm iron
C	2-1, low field, cold iron
C'	1-1, low field, cold iron
D	1-1, high field, cold iron

Table 2-1. Phase I Program Milestones.

Date	Item
Oct 1984	Define Selection Criteria and Technical Information needed for Magnet Selection
Nov 1984	Establish Primary SSC Design Features and SSC Phase I Program Plan Objectives
Apr 1985	Site Parameters Document[a]
Apr 1985	Review Magnet Development Program
Jul 1985[b]	Magnet Design Type Selection[a]
Dec 1985	Preliminary Conceptual Design
Feb 1986	Start Pre-Production Prototype Magnets
Mar 1986	Conceptual Design Report (non-site specific) and Other Documentation[a]
Oct 1986	Magnet Half Cell Test Begins
Dec 1986	Site Selection by DOE[a]
Apr 1987	Report on Half Cell Test
Aug 1987	Recommended SSC Phase II Management and Procurement Plans Partial Title I Design Report
Oct 1987	SSC Construction Start (NTP)[a]

[a] Denotes Primary Milestone

[b] Selection to be made during the last quarter of FY 1985.

studies have indicated could meet the scientific objectives and be economically competitive. The five are variants of two basic approaches, the iron-shaped field approach and the conductor-shaped field approach. Each of these is applied to a version in which the two beam channels of the collider are mechanically and cryogenically independent (1-1) and a version in which the two channels are mechanically linked within a common cryogenic envelope (2-1). These four employ magnet iron held at coil operating temperature. The fifth variant has a conductor-shaped field with the shielding iron held at room temperature. The iron-shaped field versions are limited in field to 3 Tesla or less by the properties of iron. The conductor shaped field versions are limited in field by the properties of superconducting materials. The economic optimum for this type at 4.5K appears to be at 6 Tesla or somewhat higher.

Figure 2-1 displays the various activities aimed at the final selection process, as well as the integration of the technical inputs into a selection decision. This process will be carried out in three steps. The Technical Magnet Review Panel will evaluate the technical status of design and development work on the magnets and specify the R&D remaining before each of the types under consideration is ready for final prototyping. The report of this panel, along with the cost information and information resulting from accelerator systems considerations, will be presented to a Magnet Selection Advisory Panel which will produce an ordered preference list, with justification, of the basic magnet types under consideration. Criteria to be used by the Advisory Panel include relative capital cost, operating cost, workability of designs, relative complexity of the magnet systems and of their operation, relative flexibility of SSC design employing the various magnets, impact of the magnet types on the construction schedule, remaining R&D and accelerator physics considerations. The detailed charges to the panels are contained in Appendix A.

Substantial technical progress in assessing the viability and engineering features of the various types has already been made. Of the iron-shaped types, 1-meter and 7-meter models have been tested for a cumulative total of 20 meters of beam channel. Of the conductor-shaped types, 1-meter and 4.5-meter models have been tested for a cumulative total of 45 meters of beam channel. In all cases the magnetic field achieved was a few per cent greater than that predicted from short-sample measurements of the superconducting

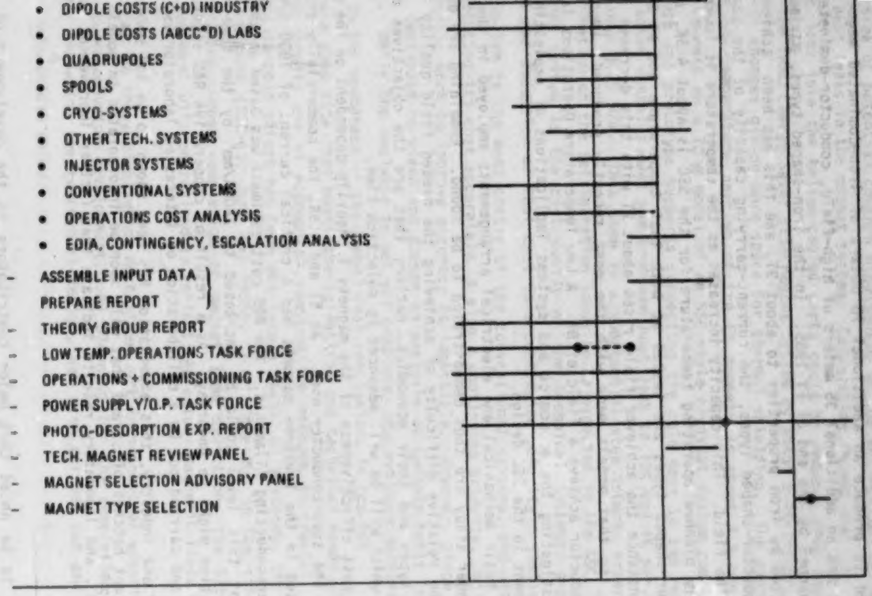

Fig. 2-1. Plan for magnet type selection.

strand used, taking into account the expected degradation from cabling and winding. Very little training is observed. Model production now in train is expected to produce an additional 70 meters of iron-dominated magnet beam channel and an additional 35 meters of high-field, conductor-dominated magnet beam channel by the end of FY 1985. In the iron-shaped types, maximum field is limited by iron properties to about 3T, and this has been achieved. In the conductor-shaped types, the current-carrying capacity of the conductor limits the field. This capacity increases as the temperature is lowered. The presently planned operating temperature for the SSC is about 4.5K, and the conductor-shaped types are tested at both that temperature and at 2K. In every instance the achieved field rises about 2T with this decrease in temperature, so that models made with the most recently produced, improved, superconductor achieve a field of 8T. A Low Temperature Operations Task Force is investigating the economics and systems implications of exploiting this improvement in the SSC design.

The basic mechanical and electrical arrangements employed in the magnet types under study are thus demonstrated to be sound. Remaining are questions about the relative difficulty of achieving the needed field quality in the various types and their economics, matters that are the objectives of the studies which will be well advanced by selection time.

The cost effectiveness of the magnets is heavily dependent on the performance of the superconductor used. At 5T and 4.5K, the commercially available cable used in the Tevatron magnets had a critical current of 1800 A/mm^2 in the superconducting filaments. The RDS cost estimate was based on the assumption that this level could be increased to 2400A/mm^2 by the time SSC construction might be underway. As a result of cooperative R&D sponsored by the DOE and carried out by a collaboration of interested laboratories, universities,* and industry, this expectation has been shown to be too modest. The most recent batches of strand that will soon be incorporated in models achieve 2700A/mm^2, and laboratory results indicate that further improvement is to be expected. The strategy for exploiting these gains in the most cost-effective way is still being mapped out. In any event, some cost decrease will result.

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* It is to be noted that major contributors to the development of the processes resulting in improved performance are the Teledyne Wah Chang Corporation in producing high homogeneity NbTi alloy, and Prof. D. Larbalestier and colleagues at the University of Wisconsin in devising improved wire-production techniques which have been successfully transfered to industry.

Another area of potential concern highlighted in the RDS was the achievement of low heat leaks in the magnet system. Calculation showed that the average heat leak into the helium-cooled parts could be reduced from those measured in the FNAL Energy Saver (ES) Magnet System by about a factor of five through design changes giving more space for thermal shielding. The average loss to the low-temperature portion of the ES magnets is about 1.5 W/m. Recent measurements on a 12 m model of an SSC-style cryostat system complete with cold mass and prototype supports connecting the cold mass to the room-temperature outer vessel showed the combined heat leak to 10K and 4K portions to be less than 0.25 W/m. This then is a substantial step towards experimental verification of the refrigeration loads to be expected in the SSC.

The magnet system is the most costly of the technical systems, and verification and reduction of that cost is a continuing priority. Similarly the tunnel system is the most costly of the conventional systems, and attention to predicting its cost accurately is also a continuing priority. Without a site, specific work to improve accuracy is impossible. However, since the RDS we have continued to widen and deepen an analysis of tunnels built in the recent past. While the analysis is not yet complete, the evidence gathered so far points to the soundness of the tunnel cost conclusions in the RDS.

Securing a good site that meets the scientific and technical needs of the facility and permits use of economical construction methods is crucial. To this end considerable effort has been put into a technical advisory, the Site Parameters Document (SSC-15, June 15, 1985), to aid the DOE in the site-selection process. Upon completion of magnet type selection, the Site Parameters Document will be revised to reflect the actual magnetic field value selected.

In addition to these highlights, much other work in support of magnet type selection, superconductor development, and planning for the completion of Phase I R&D, including the conceptual design, has been carried out and is reported in more detail below.

2.2 Agreements on R&D Tasks, Budgets, Costs in FY 1985

The planned program for the SSC in FY 1985 involves primarily the CDG and BNL, FNAL, LBL, TAC, and some industrial contracts. The CDG has the responsibility for organizing, planning, and coordinating all R&D for the SSC Phase I program (See Chapter I). Efforts for the magnet program in FY 1985 involve coordination of laboratory programs and also the planning and analysis required for the selection of a magnet style. In the area of accelerator physics studies, the CDG staff, with assistance of personnel from other institutions, plays a central role. Specific details of these activities and accomplishments are given in the following sections of this report under Accelerator Physics, Accelerator Systems, Conventional Systems, and Magnet Systems. The planned CDG budget for FY 1985 follows these categories and is summarized in Table 2-2 below.

Table 2-2 SSC Central Design Group Budget Plan (M$).

	FY85
Administration and Support	2.01
Project Planning and Management	0.40
Accelerator Physics	0.68
Magnet Program	0.50
Accelerator Technical Systems	0.50
Injection Systems	0.05
Conventional Systems[a]	1.18
Total	5.32

[a] Includes engineering study contracts.

The primary tasks to be performed by each of the participating institutions, as set forth in the performance agreements with the CDG, are outlined below.

Brookhaven National Laboratory

The primary tasks to be performed by BNL in FY 1985 are:

1. Completion of field-quality measurements on 3.2-cm bore, 2-in-1, NbTi magnets.
2. Construction and test, in collaboration with others, of at least four 4-cm bore, single-channel, cold-iron magnets of length sufficient to demonstrate basic mechanical and thermal properties.
3. Study of quench-propagation characteristics of various coil assemblies.

4. Study of cold diodes suitable for passive quench protection.
5. Continue, in collaboration with others, studies of fine-filament NbTi superconductor production.
6. Provide detailed design information, by Feb. 15, 1985, for 2-in-1 and 1-in-1 cosine-theta magnets sufficient for cost estimating and reliability analysis purposes. A magnetic design for a 2-in-1 quadrupole is to be included.
7. Carry out 4-cm bore-tube development, including high-conductivity inner coatings, special cooling for synchrotron radiation load, and bore-tube-attached correction-coil packages.
8. Provide facilities for and participate in photodesorption experiments relevant to SSC vacuum requirements.
9. Carry out preliminary planning of and make preliminary arrangements for carrying out the Long String Test and Short String Test as defined in SSC-SR-1001.
10. Participate in accelerator physics studies in support of aperture determination and preliminary conceptual design.

Fermi National Accelerator Laboratory

The primary tasks to be performed by FNAL in FY 1985 are:

1. Provide design support for the national cosine-theta magnet effort.
2. Design and develop a "dry-wound" coil-insulation system and test with appropriate 1-meter models. Provide wet-wound coils as required for cryostat tests.
3. Design and develop cryostat for 1-in-1 type cosine-theta magnets.
4. Provide design information needed for cost and reliability analysis of 1-in-1 "ironless" and cold-iron magnets of cosine-theta type.
5. Continue, in collaboration with others, development of high-current-density superconductor.
6. Carry out preliminary planning of and make preliminary arrangements for carrying out a Magnet Half Cell Test.
7. Provide support of CDG Aperture Task Force and preliminary conceptual design activities.
8. Provide support of CDG Photodesorption Task Force.
9. Conduct studies of modifications and additions to Tevatron which would be required in the event it is needed for SSC injector service.

Lawrence Berkeley Laboratory

The primary tasks to be performed by LBL in FY 1985 are:

1. Fabricate and test eight 3-foot superconducting accelerator magnet models per specified schedule.
2. Develop neutral coil-end designs.
3. Direct work of industrial consultants in cryostat design for cosine-theta magnets.
4. Continue superconductor and cable studies to improve annealing procedures; the goal is to produce fine-filament NbTi with J_c above 2400A/mm^2. LBL will also supply the strands and cable for both the LBL and BNL programs.
5. Assist CDG in magnet-design and cost-estimating activities.
6. Accelerator theory support to the CDG including participation in the National Magnet Aperture Task Force directed by the CDG. This effort will supply at least six FTE accelerator physicists to work on the general lattice, aperture, and machine-design problems for an SSC.

Texas Accelerator Center

The primary tasks to be performed by TAC FY 1985 are:

1. Fabricate and test superferric accelerator magnet models per specified schedule.
    - (a) Ten or more 30-inch one-channel segments either coupled or uncoupled.
    - (b) Four or more 25-foot 2-in-1 models.
    - (c) Three approximately 92-foot 2-in-1 models (subject to accomplishment of a successful arrangement for assembly by others).
2. Accomplishment by February 15, 1985, of detailed designs and specifications for:
    - (a) 2-in-1, 1"V x 1.3"H aperture dipoles
    - (b) 2-in-1, 1" x 1.6" aperture dipoles
    - (c) 1-in-1, 1" x 1.3" aperture dipoles
    - (d) 2-in-1 quadrupoles with computations of B(r,θ) as a function of excitation currents equivalent to 1 TeV, 10 TeV, and 20 TeV operation.

    In this context 1-in-1 means magnetic, electrical and quench independence of the beam channels.
3. Accelerator theory support in the form of participation in the National Magnet Aperture Task Force directed by the CDG. This effort will supply at least two FTE accelerator physicists to work on the general aperture problems for an SSC.

The above tasks were developed at the beginning of FY 1985 with particular reference to Magnet Designs A, B, and C and modifications thereof. In December 1985, Magnet Design D, a 1-in-1 design incorporating B coil design into cold iron of A, was proposed with a collaborative arrangement between BNL, FNAL, and LBL. The plan for Magnet Design D and the specific Laboratory responsibilities are summarized below.

BNL-FNAL-LBL Magnet Design D

The short-range program plan for each Laboratory is as follows:

BNL

(a) Build four to six 1-in-1 4.0-cm-aperture magnets on same schedule as former 2-in-1 plan.
(b) Continue development of bore tube including coatings, special cooling for synchrotron-radiation effects, correction coils, etc.
(c) Develop magnet-measuring hardware.

FNAL

(a) Develop and design a "dry-wound" coil-insulation system and test with appropriate models.
(b) Develop and design the cryostat for the "long" [and possibly short (4.5 meter)] magnets.

LBL

(a) Continue fabrication of 1-meter models to confirm coil cross section and collaring approach.
(b) Develop appropriate end shape for NbTi coils (non-dog bone).
(c) Continue development of improved wire and cable.

The longer range program for Design D, while dependent on available funding, would be expected to include the following plan:

(a) Joint development of "long" magnets.
(b) Magnets will use more optimized NbTi, optimized iron, optimized ends, collars to accommodate "dry" and "wet" coils.
(c) Jointly developed high-current-density fine-filament NbTi wire.
(d) FNAL will build cryostats (at least 4).
(e) BNL will build collared "wet" coils with LBL ends (at least 4).
(f) FNAL will build "dry" collared coils (at least 4) using BNL collars.
(g) Parts for 10 more "long" magnets will be procured for fabrication in FY 1986.

The budget and reporting categories for each of the participating institutions were reviewed by the Fiscal and Managerial Task Force in November 1984. The resulting established budget categories for each institution are found in Table 9-5, p. 120.

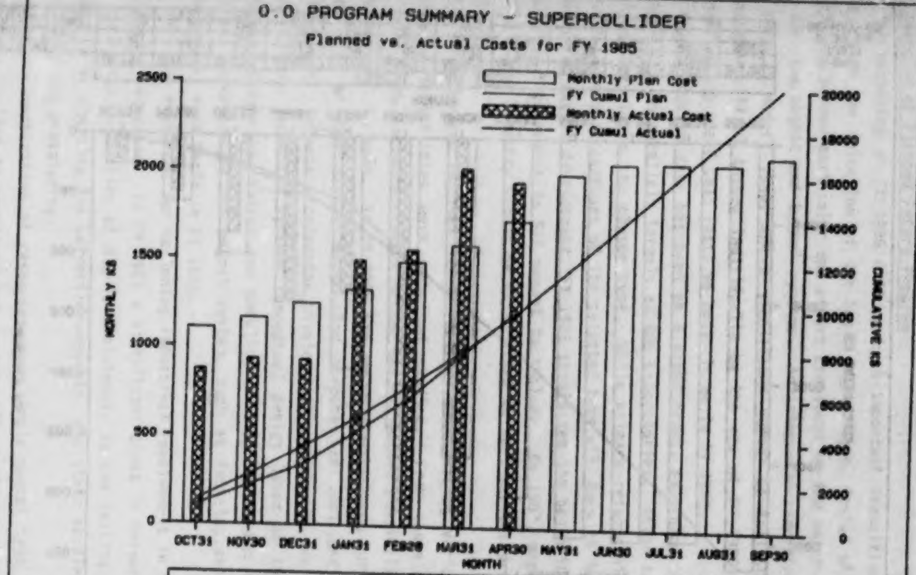
A summary of the R&D costs by institution is shown for the SSC program and for related Laboratory accelerator programs in Tables 2-3 and 2-4. The cumulative costs and the monthly costs are graphically displayed in Figs. 2-2 and 2-3. The projected SSC funding level for the first seven months of operation was $9.67M. The actual costs were $9.78M as shown in the table at the bottom of Fig. 2-2.

Table 2-3. Program Summary - SuperCollider.
April 1985 Cost Report (K$)

	Program Element	Year to Date	Annual Budget
1.	CDG Program	2068	5325
2.	BNL SSC Program	3085	4980
3.	FNAL SSC Program	2519.9	3905
4.	LBL SSC Program	464	790
5.	TAC SSC Program	1640.6	5000
	Total SSC Program	9777.5	20000

Table 2-4. SSC-Related Accelerator Program Summary.
April 1985 Cost Report (K$)

	Program Element	Year to Date	Annual Budget
1.	BNL	910	1670
2.	FNAL	1628.7	2120
3.	LBL	708	1210
	Total SSC Related	3246.7	5000



	FISCAL YEAR 1985											
	OCT31	NOV30	DEC31	JAN31	FEB28	MAR31	APR30	MAY31	JUN30	JUL31	AUG31	SEP30
Monthly Plan	1106	1166	1241	1341	1483	1543	1693	2100	2069	2071	2071	2116
FY Cumul Plan	1106	2272	3514	4855	6338	7881	9574	11674	13743	15812	17883	20000
Monthly Actual	872	935	931	1498	1561	2026	1927					
FY Cumul Actual	872	1807	2738	4236	5797	7823	9750					

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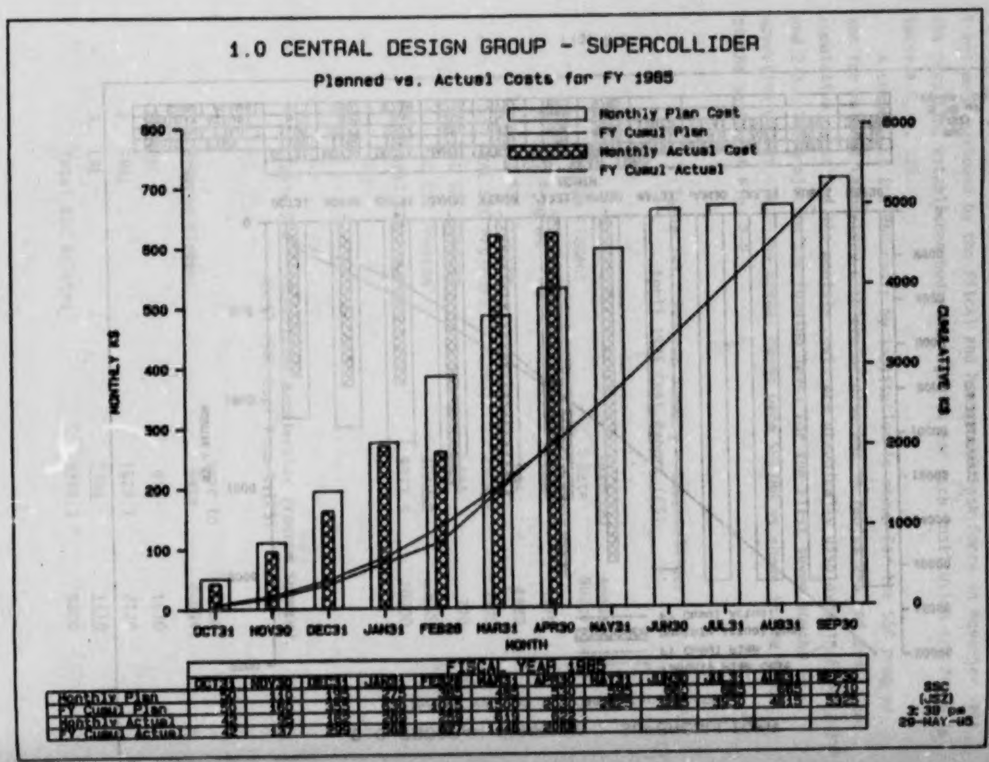
Fig. 2-2



	FISCAL YEAR 1985											
	OCT31	NOV30	DEC31	JAN31	FEB28	MAR31	APR30	MAY31	JUN30	JUL31	AUG31	SEP30
Monthly Plan	50	110	[illegible]	275	[illegible]	485	530	[illegible]	[illegible]	[illegible]	665	710
FY Cumul Plan	50	160	355	630	1015	1500	2030	[illegible]	[illegible]	3950	4615	5325
Monthly Actual	42	95	162	[illegible]	[illegible]	619	622					
FY Cumul Actual	42	137	299	568	827	1446	2068					

Fig. 2-3

2.3 Overview of Planned Future Program

The beginning of FY 1986 will mark an important transition in SSC R&D work. With the selection of the basic magnet type, design of the overall system can become particular and effort can focus on the major cost items of the SSC, the magnet and tunnel systems. An integrated conceptual design will be ready by mid-FY 1986, and a significant number of full-scale magnet prototypes will be tested individually by the end of FY 1986 with magnet system testing (Half Cell Test) to begin in early FY 1987.

Magnet work to date has been on a broad front, examining several magnet technologies in parallel, largely at DOE Laboratories. After selection, work will concentrate on the chosen type. While primary responsibility for the first full-scale prototypes of the selected type will be with laboratories now involved in magnet development, FY 1986 should see the beginning of a strong industrial involvement in SSC magnet technology. By 1987, magnet prototype production in industry should be established so that serious production could begin in 1988.

In FY 1984 and FY 1985 sketch designs encompassing various magnet technical possibilities were made and studied. From these and from engineering and hardware studies of the several magnet possibilities, a magnet selection will be made. In FY 1986 the emphasis will be on further technical development of the dipole magnet for purposes of cost and design verification. Intense accelerator physics and engineering design work will flesh out the technical systems conceptual design based on the selected magnet. Engineering studies and modeling of less costly but technically critical components of the magnet system, such as focusing and correction magnets, will also begin in FY 1986.

Increased resources for beginning industrial involvement in SSC magnets in FY 1986 are requested. In FY 1987 a significant boost in resources is needed for industrial production of dipole prototypes, system testing of dipoles, production of focusing and correction magnets, and other accelerator system development and prototyping.

Through concentration of resources on a single magnet type, it will be possible in FY 1986 to construct and individually test enough SSC prototype magnets for one half cell. These magnets will be assembled into an array for the Half Cell Test beginning in FY 1987. By this means, the engineering viability of the magnet design will be explored and material quantities firmly established. The initial prototyping experience at the laboratories, coupled with the growing industrial involvement and its associated manufacturing studies, will serve to establish tooling and labor costs.

Accelerator systems and accelerator physics work in FY 1986 will focus on the production of a viable, technical conceptual design from which a detailed cost estimate can be made. In the latter part of FY 1986 and through 1987, work in these areas will emphasize certain critical-component R&D, system testing of the magnets and associated instrumentation, and developing detailed systems and systems-interface specifications to provide a very detailed picture of the SSC technical systems.

Owing to their considerable cost impact, conventional systems will also receive further attention. A non-site-specific integrated design will be worked out to identify all principal structures; a general site master plan for optimized adaptation of conventional structures to the scientific and technical needs of the facility will be devised; cost sensitivities to geology, topography, and construction method will be investigated.

To round out the picture of what the full SSC project would entail, considerable planning of engineering development, fabrication, installation, and sequencing is needed. This activity, including the study of critical-path networks and quality-control plans, will be an important effort of the Project Planning and Management Division. From these efforts possible schedules and resource-need profiles will be developed, showing how the R&D program could interface with the beginning of construction.

Milestones and goals are shown in Fig. 2-4. Detailed projected time lines for these activities are displayed in Figs. 9-1 through 9-5 at the end of Section 9.2.

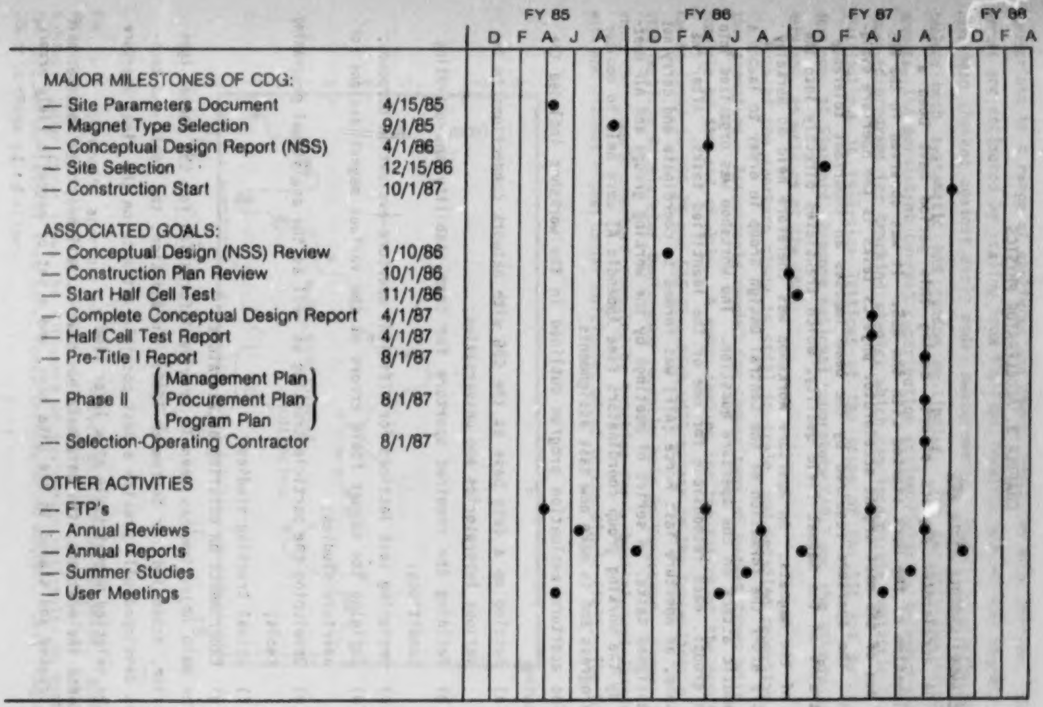


Fig. 2-4. SSC Milestones and Goals

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CHAPTER 3. ACCELERATOR PHYSICS

3.1 Accomplishments Since RDS

The accelerator physics efforts during this period have been a continuation of the work started with the RDS. It was observed in the RDS that one of the most urgent accelerator physics tasks is the aperture evaluation. The aperture required by the beam imposes an important tolerance constraint on the magnet field quality, which translates directly into the cost of the magnets. An Aperture Workshop was therefore held at Berkeley shortly after the formation of the Central Design Group in order to launch a systematic attack on the aperture question. The workshop was organized into seven groups, each responsible for one of the identified tasks. After the workshop, an Aperture Task Force (ATF) was formed to coordinate and carry out the assigned tasks. A series of meetings by the working groups and ATF meetings by the working group coordinators (see Appendix A) were held to monitor the progress and to make new task assignments.

The aperture evaluation program outlined in the workshop included the following:

(a) Setting up a data base at the CDG with network connections to the various laboratories and universities;

(b) Defining the required aperture for beam stability and operating conditions;

(c) Designing test lattices for efficient aperture-evaluation purposes;

(d) Defining the magnet field errors of the various magnet designs for aperture studies;

(e) Developing the particle-tracking as well as the analytical programing tools;

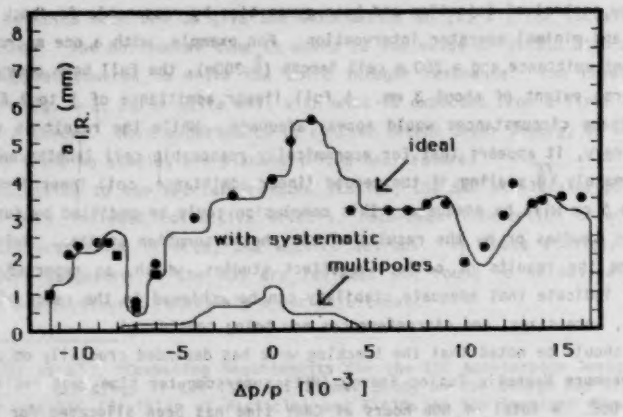
(f) Actual tracking studies;

(g) Experiments on existing accelerators.

The main objective has been to provide information for the magnet type selection, scheduled for September 1985. In addition, the tools and techniques developed will provide a best possible estimate on the final aperture for the selected magnet style at a later time.

Since the workshop, the data base has been established, test lattices have been created and stored in the data base, and a set of magnetic field errors opriate to a range of apertures and magnet types has been derived. These rs are estimated by scaling from the FNAL Tevatron and BNL CBA magnets and been checked against early model measurements. The field descriptions lude both systematic and random multipoles. For conductor-dominated ets, the persistent current contribution at low fields is included also. roved programs for tracking studies which can incorporate realistic error tributions in full-size lattices of the scope of the SSC are being eloped at Stanford, Argonne National Laboratory (ANL) and the University of yland, as well as at the CDG.

Much of the aperture study is still in train, and detailed reporting is premature. Assessments needed for comparisons of magnet types will be plete by the end of July. A rough feeling for the nature of the results be found in SSC-24 and SSC-25, which will appear in the Proceedings of the 5 Particle Accelerator Conference recently held in Vancouver. Figure 3-1 ws the dynamic aperture computed by tracking for a typical test lattice h and without higher order multipoles added to the dipole field. The ideal



. 3-1. Chromatic aperture of TLA1 lattice at interaction point. DIMAT a are given by solid lines, PATRICIA data by circles, and MARYLIE data by ares. Lower curve shows the influence of systematic multipoles on dynamic rture in the case of 4-cm bore, conductor-dominated magnet. Cell length is m in these calculations.

case incorporated ideal dipoles, quadrupoles, and chromaticity-correcting sextupoles. The stable oscillation amplitude is recorded at the crossing points. The corresponding stable amplitude in the bending dipoles is obtained by multiplying by 17.3. In the case shown, the potential dynamic aperture of the ideal machine is considerably larger than the physical aperture. When the multipole content of the dipoles is included, the dynamic aperture shrinks substantially but is still sufficient to meet SSC requirements. Further study using shorter cell lengths is indicated. It appears that stable amplitudes up to about 1 cm in the arcs can result if $\Delta B/B$ of less than a few parts in 10^4 is achieved at 1 cm radius.

For assessing the physical aperture requirements of the magnets, the concept of "linear aperture" is useful. The linear aperture is defined by those amplitudes for which beam response is essentially linear, i.e., smearing of amplitudes from turn-to-turn is small (less that 10%) and betatron tune deviates by no more than 0.005 from the infinitesimal amplitude frequency, all for fractional momentum deviations less than 10^{-3}. Efficient operation demands that this aperture be larger than the natural beam size at injection to allow control of injection and beam gymnastics by reasonable feedback techniques and minimal operator intervention. For example, with a one micrometer invariant emittance and a 200 m cell length ($\hat{\beta}$=300m), the full beam occupies a transverse extent of about 3 mm. A full linear admittance of 1 to 1.5 cm under these circumstances would appear adequate. While the result is very preliminary, it appears that for economically reasonable cell lengths and for approximately $\sqrt{\hat{\beta}}$ scaling of the needed linear admittance, coil inner diameters of 4 to 5 cm will be adequate. This conclusion could be modified by further tracking studies or by the results of the photodesorption studies. Relevant also are the results of collective-effect studies, which, as reported in SSC-25, indicate that adequate stability can be achieved in the range of cell lengths, bore sizes, and circumferences now being considered.

It should be noted that the tracking work has depended crucially on use of the Livermore Magnetic Fusion Energy (MFE) supercomputer time made available by the DOE. A total of 806 hours of CRAY time has been allocated for SSC design computations for FY 1985. So far, 412 hours have been consumed. The remaining hours are expected to be used up by the end of the fiscal year.

During this period, it has been necessary to develop quickly the design programs at the beginning of the year and then to use the allocations carefully, minimizing the number of runs while trying to obtain sufficient information. Computing has been concentrated mainly on the aperture evaluation needed for magnet selection.

As the design studies proceed, computation of other effects will consume more time, while the aperture computations will continue. For the next fiscal year, it is not expected that the present CRAY allocation will be adequate. At the peak of SSC design efforts, the needed CRAY time will be more than 2000 XMP hours per year, as estimated by the DOE subpanel on computing needs for high energy physics.*

A major purpose of accelerator experiments addressing the aperture issue is to supplement and check tracking codes and their computations. In the past, such studies have also revealed phenomena not predicted in the numerical simulations. To this end, experimental efforts are now underway at SPEAR and the Tevatron and initial results are at hand.**

In the initial Tevatron experiment, the beam positions are measured by two nearby position monitors to give the information on (x, x') for successive revolutions. The horizontal tune is moved to the value of 19.333 with a set of sextupoles powered to drive the third integer resonance. The results, shown in Fig. 3-2, agree quite well with what is expected from a first order resonance theory. More experiments to confirm second order theory, as well as detailed tracking studies are planned in the near future.

In addition to the aperture-related studies, the SSC accelerator physics studies have included collective effects, beam-beam interaction effects, intrabeam scattering effects, and lattice designs. In these studies, the parameters suggested in the RDS are reviewed and found to be basically optimized with several relatively minor adjustments.

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*A. Dragt et al., "Computing Requirements for the SSC Accelerator Design and Studies," Proceedings of the 1984 DPF Summer Study on the Design and Utilization of the SSC (Division of Particles and Fields of the American Physical Society, 1985), Snowmass, Colorado, p. 395.

**(a) D.A. Edwards, R.P. Johnson and F. Willeke, Fermilab-PUB-85/59 (1985) "Tests of Orbital Dynamics Using the Tevatron". (b) F. Willeke, TM-1309 (1985), FNAL internal note, "Using the Tevatron Beam Position Monitor System to Investigate Transverse Phase Space". (c) P.L. Morton et al, SPEAR group, SLAC-PUB-3627 (1985) "A Diagnostic For Dynamic Aperture".

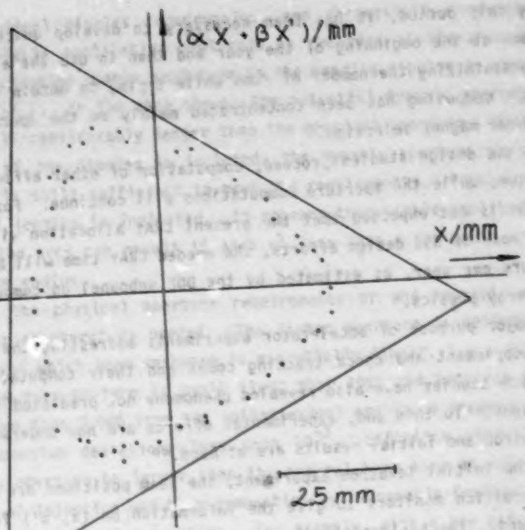

Fig. 3-2. The x, x' plot observed for successive turns in the Tevatron for a tune near a third integer (19.333) with sextupoles powered to drive the third integer resonance. The triangle drawn on the figure is the calculated limit of stability, the separatrix.

In anticipation of the Conceptual Design Report in April 1986, an effort has been initiated to create a detailed "realistic" lattice design that takes into account all known accelerator physics and systems requirements up to date. This effort was begun with a workshop at the CDG on May 29-June 4.

It is necessary to explore the various possible options for the SSC with proper priorities. These include clustered interaction region designs, pp option, polarized beams, ep option, fixed targets, unbunched beams, etc. Extensive studies were made at the 1984 Snowmass meeting* on these options.

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*Proceedings of the 1984 DPF Summer Study on the Design and Utilization of the SSC (Division of Particles and Fields of the American Physical Society, 1985), Snowmass, Colorado.

e CDG, in parallel with the realistic lattice effort, a study was started
aluate the implications of clustered interaction regions for the SSC.
study group has held two meetings in April and June (see Appendix A).
lan is to make an explicit recommendation in September for inclusion in
stic lattice design considerations.

lans for FY 1986 and beyond

fter the selection of the basic magnet design, the most immediate goal of
erator physics studies is support of the effort on the Conceptual Design
t scheduled for April 1986. To help the conceptual design, a first step
establish an initial list of parameters during October 1985. Such lists
given in the RDS. The list for the chosen type of magnet will benefit
the studies briefly described in Section 3.1. Such a list will also help
ccelerator systems and the conventional facilities designs.

ne of the more important elements of the parameter list is the lattice
n. As mentioned in Section II.2, an effort has already been started to
e a realistic lattice for each of the possible magnet types which takes
account detailed accelerator physics and systems considerations. It is
ted that a realistic lattice design will be available at the time of the
ial parameter list.

he study of the various options for the SSC needs to proceed in a timely
ion. The option of clustered interaction regions has been started at the
since it has potentially the most extensive impact on the overall concep-
design. The study group will make its first recommendation to the CDG at
t the time of the magnet selection. The realistic lattice to be presented
ctober will take into consideration both the magnet selection and the
mendation from the clustered IR study group.

Once the initial lattice and the initial parameter list are established,
accelerator physics studies will proceed in several directions: further
ture evaluation, collective effects, lattice design, options studies,
-beam effects, operation and systems issues, and boosters and linac issues
master plan). The results of these studies will be communicated to the
r studies in parallel and when applicable will appear as changes in the

parameter list. The parameter list acts as a brief summary of the current conceptual design. An interim review of the parameters will be held approximately in January 1986. As time proceeds, the lists will firm up.

Shortly before the Conceptual Design in April 1986, the various accelerator physics studies being carried out will be described in technical reports. The studies to be included are listed below in some detail:

Aperture Evaluation

- networks, data-base maintenance
- field-quality studies (tolerances, trade-off between multipoles, correction of multipoles)
- test lattices
- analytical techniques for aperture evaluation (conventional perturbation theory, Lie algebraic techniques, nonlinear Hamiltonian dynamics)
- program developments, both analytical and tracking programs (Lie algebra codes, kick codes)
- tracking studies (linear aperture, dynamic aperture)
- dedicated processors when applicable

Collective Effects

- impedance calculations (analytical and numerical calculations, 2- and 3-D programs)
- impedance budget (bellows, pick-up electrodes, 4.5K copper resistive wall, rf cavities, kickers, beam separators)
- instability threshold and growth rates (analytical calculations, numerical simulations, needed energy aperture, multi-bunch instabilities, mode coupling, feedback requirements, choice of synchrotron tune)
- intrabeam scattering, Touschek effects (needed energy spread, rf requirements)

Lattice Design

- interaction-region optics (quadrupole arrangements, IR hall requirements, free space for detectors)
- cell optics (cell length optimization, phase advance per cell)
- utility sections (rf, injection, abort and beam scraping sections)
- sextupole schemes (number of families, chromatic aberrations)

Parameters and Options

- parameter optimization (overview, scaling laws)
- options (clustered IR, $\bar{p}$-p, polarized beams, ep, fixed target, alternative acceleration schemes, unbunched beams, terrain following)

Beam-beam Effects

- beam-beam limit (head-on tune shift, resonance widths)
- crossing-angle and long-range effects (bunch spacing, orbit and tune-shift effects, synchrobetatron resonances, coherent beam-beam effects, Pacman effect)
- tracking simulations (crossing angle, simulations with and without lattice errors, coherent and incoherent effects)

Operation and Systems Issues

- operation requirements (linear aperture, first turn, abort trigger, detailed acceleration procedure, bring beams in/out of collisions, computer simulations)
- rf specifications (injection chain, rf noise, transient beam loading, impedance)
- systems elements (realistic lattice, spool-piece definition, orbit-correction scheme, feedback systems, impedance budget, magnet specifications)
- tolerance specifications (magnet alignment, magnet strength errors, multipole tolerance, power-supply ripple, survey errors, beam-position-monitor errors, ground motion, numerical simulation of error effects)
- magnet shuffling

Boosters and Linac

- lattice designs
- collective effects (instabilities in the boosters, space-charge effects, beam break up in linac, gun design)
- emittance budget

After the Conceptual Design Report, it is important to continue the accelerator physics studies along the same lines described above. For example, as the site selection is made, the studies will take into consideration the site-specific issues such as terrain following. As the detector needs are specified, the interaction region optics will be modified. In addition, detailed parameter optimization will continue to require studies to be made on the various accelerator physics issues such as the lattice and the beam-beam and collective effects.

Assuming the availability of adequate resources, the above mentioned studies will be carried out in depth after the 1986 Conceptual Design, leading to a Final Conceptual Design in April 1987.

CHAPTER 4. ACCELERATOR SYSTEMS

4.1 Issues at time of RDS

The Reference Designs Study was primarily concerned with getting a cost estimate for sample SSC designs and determining if there were any indications of significant difficulties in design, construction, or operation. The result of the study was that the SSC is feasible with present day technology, but that there are a number of engineering questions that should be answered in order to design and develop cost-effective, reliable, and high-performance collider rings. The most important issues that affect the Accelerator Systems Division (ASD) of the CDG are listed below:

1. Magnet Selection.

Because of the success of the Tevatron, there is no longer any doubt that magnets of sufficient quality and performance can be produced in quantity. The issues that remain are:

(a) The choice of a magnet type that will result in a cost-effective, reliable, and high-performance multi-TeV collider, without excessive R&D.

(b) The effects of a particular magnet type on the designs of the accelerator systems.

2. Systems Tests.

Whatever the magnet type, it will be important to test the prototypes and the production magnets as systems in order to detect design flaws and to determine that the magnet system is able to be integrated into all the other systems that make up the SSC. Tests of strings of magnets are also an important tool in the development of the various accelerator systems. A systems test program must effectively address:

(a) The development of a cost-optimized, but conservative and reliable, magnet system design.

(b) The utilization of string tests as an effective test and development tool for the whole accelerator system.

3. Cryogenics.

The cryogenic systems that were sketched out for the RDS assumed that the magnet cryostats would have a static heat load to 4.5K that was at least a factor of five smaller than the Tevatron. In addition, there were three distinct cryogenic system designs presented in the RDS, none of them optimized.

The major issues of a cryogenics R&D program are:

(a) The development of a cryostat for SSC magnets with sufficiently low heat loads.

(b) The optimization of the cryogenic systems and refrigerators, based on commercially available components.

(c) The feasibility of operating the magnet system at temperatures lower than 4.5K to obtain higher field (and therefore higher energy or the same energy with a smaller ring).

4. **Vacuum.**

Good beam lifetime requires ultra-high vacuum. The SSC's energy is sufficiently high that the protons emit a considerable amount of synchrotron radiation, one result of which will be to desorb gas from the beam-tube walls. Because there are very little data on photon-induced desorption from cryogenic surfaces, it is necessary to mount a R&D effort to obtain the required information on the expected gas density from synchrotron radiation.

5. **Beam Losses.**

Its very high luminosity makes beam loss a particular problem for the SSC. With clustered interaction regions, there is a potential exacerbation of the problem because of the creation of a beam halo by small angle elastic scatterings. Beam loss concentrated in one area can cause quenches that would be disruptive to the research program and to the cryogenic and magnet systems. The R&D effort on beam losses must investigate:

(a) The effects of beam loss from one interaction region to another for various arrangements of the lattice and interaction regions.

(b) The optimum design and location for beam scrapers.

(c) The radiation intensity and spectrum in the tunnel, and the resulting effect on electronics and materials used in the magnets.

(d) An effective design of the injection and beam-abort systems to minimize beam loss.

6. **Reliability.**

The great size and large number of components of the SSC, together with the need for operational availability, make it imperative that all the systems work reliably. The Tevatron provides a model from which a reliability data base can be established and extrapolations made to the SSC. The R&D program should address:

(a) The interpretation of the existing data on accelerator reliability regarding the SSC's construction, commissioning, and operation.

(b) The potential for increased operational availability by improved design, development, and testing, and at what capital and operating cost.

7. Cost Estimates.

The cost estimates of the RDS can be improved and extended in a number of ways. In particular, the estimates of the systems costs were carefully done only for one of the designs, and were based on general rules, not on quotations from vendors. Cost issues needing early R&D are:

(a) Costs of the accelerator systems that are specific to each of the possible magnet types, preferably based on vendor quotations.

(b) Reliable scaling rules to understand the sensitivity of the machine designs to possible changes.

4.2. FY 1985 Activities Bearing on Magnet Type Selection

The tasks assigned to the ASD for the magnet type selection are listed in Table 4-1. They concern the reports of two task forces that were formed to study the effects of the different magnet types on commissioning and operations

Table 4-1. ASD Tasks for Magnet Type Selection.

	Title	Date Due
1.	The Report of the Task Force on Commissioning and Operations of the SSC	June 1985
2.	The Report of the Task Force on Power Supplies and Quench Protection	June 1985
3.	A Preliminary Report on the Photodesorption Experiment for cryogenic beam tubes	August 1985
4.	Analyses of the costs of the systems and installation for the various magnet types	August 1985

of the SSC, and on the design of the power supply and quench protection systems. In addition, there are two other aspects of the early R&D that will influence the magnet type selection: (i) the results of the photodesorption experiment, and (ii) some new cost estimates. These are listed in the table above, and are discussed in more detail later in this chapter.

A Task Force on Commissioning and Operations was formed in January, 1985 to study the commissioning and operating characteristics of collider rings constructed from the various magnet designs (see Appendix A for membership, schedule, etc.). A Preliminary Report of the Task Force on Commissioning and Operations was submitted to the SSC Director on May 20, 1985. The final report is due on July 1. The preliminary conclusions of the Task Force are:

- Machines with reasonable operational characteristics can be built with any of the magnet types now under development.
- There are real differences among the magnet types that result in variances in operational behavior, flexibility, and operating costs.
- One-in-one magnet types are preferred over two-in-one types for their greater flexibility, ease of operation and commissioning, and a number of design details of the complete machine. These factors are considered more important than having fewer cryostats, the major advantage of two-in-one types
- Over/under magnet configurations are preferred to side-by-side configurations, when considering one-in-one types, because of better use of tunnel space and easier installation and replacement. There are also more options for configuring the injection and abort functions for either two-in-one or one-in-one magnet types.
- There is no obvious choice to be made at this time between low-field and high-field magnet types. From the designs presently available, it appears that the low-field design results in a machine that is 5% to 10% more costly to operate than a ring made out of high-field magnets. However, there are other issues, such as synchrotron radiation and collective effects, which may be more important than the operating cost, and have yet to be completely evaluated.

During the studies conducted for magnet type selection, it became obvious that the CDG would need detailed information about the power supply requirements and the quench behavior of the different magnet types. A Workshop on Power Supplies and Quench Protection was held at the CDG on April 1-5, 1985 (see Appendix A for membership, etc.) and at the end of that workshop a report was submitted containing the results of the preliminary studies and an outline of the needed continuing work. A final report is due by July 1, 1985. The issues that were studied are:

- The behavior of the multiple power supplies of the superferric design, particularly taking into account the strongly coupled coil configuration.
- The capability of attaining the required power supply regulation. It appears that a regulation of $\Delta I/I \approx 10^{-5}$ will be necessary to maintain the tune within an acceptable range.
- An investigation of the expected transmission-line behavior of the power supply and magnet system.
- Agreement about the input parameters that should be used for the quench-propagation calculations.
- A study of questions of passive quench protection, such as the maximum permissible magnet length, the required sensitivity of detection schemes, and the quench-propagation velocities.
- The pressure rise in cryostats during a quench, especially in the high-field magnets.

4.3. Cryogenics.

Since the RDS, a considerable amount of work has been done to answer the questions about the cryogenic system. Work on the cryostat has taken place at FNAL, including the testing of model cryostats. Design of the refrigerator cycle has been done at BNL and at Cryogenic Consultants, Inc. (CCI). The work on cryostats is described in detail in Section 5.4.

Figure 4-1 shows the relative heat leak of the FNAL model cryostat as a function of pressure in the insulating vacuum. It doubles at 5×10^{-3} Torr, a very high pressure, indicating that the thermal multilayer insulating blankets are very effective. The equivalent for the Tevatron is about 2×10^{-5} Torr to double the heat leak.

The total heat-leak measurements are shown in Table 4-2. The 80K and 10K results look very good compared to calculation. The 4.5K result is not as good, being high by a factor of two. However, it is known from other tests that the heat intercepts on the support columns are not at the expected 10K, even though the shield is at 10K, and this accounts for most of the extra heat load.

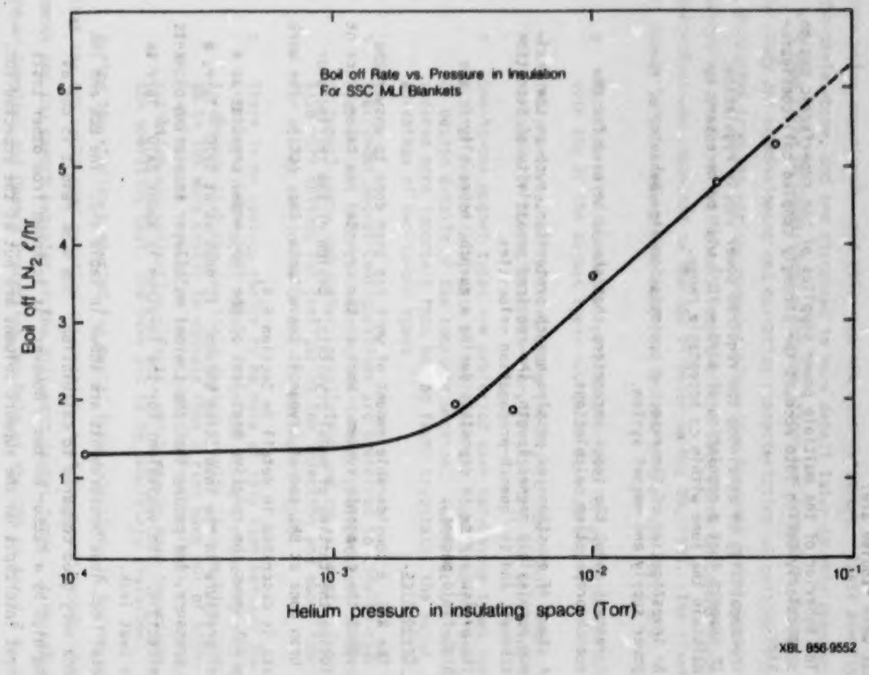

Fig. 4-1. Liquid nitrogen boil-off rate vs. pressure in insulation region of the Heat Leak Model Cryostat.

Table 4-2. Preliminary Results on Heat Leaks (in watts) from 12 m Thermal-Effects Model Cryostat.

ature	Calculated or Auxiliary Prediction		Measured Value	Measurement Method
K	End vessels (measured)	22.0		Boil off
	Thermal radiation (calculated)	8.3		
	Support conduction (calculated)	21.2		
		51.5W	55.5W	
K	Thermal radiation (calculated)	0.74		temperature rise of gas stream
	Support conduction (calculated)	1.54		
		2.28W	2.28W	
K	End vessels (measured)	0.450		Boil off
	Thermal radiation (calculated)	0.002		rate of rise of temperature of cold mass
	Support conduction (calculated)	0.125		
		0.577W	1.060W	

A group involving people from FNAL, BNL, LBL, and General Dynamics has formed to start the design of a type D cryostat. A preliminary design of cryostat for cost estimating is done, and a design criteria document is in fourth revision. The design criteria are used as a guide for the final stat design work.

Work on modeling the efficiency of the cycle used in the refrigerator system is underway at BNL and CCI. All the designs now use essentially the same system, with pressurized single-phase liquid in the coil region, returning cold gas or single-phase liquid to the refrigerator. The use of two phase return fluid is no longer present in any of the designs.

There are differences in the designs that reflect the opportunities presented by the different magnet types. The one-in-one types, for example, use the fact that there are two separate cryostats to supply the shield cooling in one cryostat and return it through the other cryostat shield. This allows the refrigerator to supply the shield flow at a higher temperature than 4.5K, without needing a separate pipe, resulting in a much higher Carnot efficiency, and therefore less operating cost. The similarity of the designs allows work to proceed to the next level of design, so that the cost estimates can be made more exact without waiting for the magnet type selection.

The development of Design D has made it necessary to understand how to remove the heat generated in the coils by the synchrotron radiation. There must be large flow paths in the cold iron for cooling the mass. This robs flow from near the coils during operation. Studies show, however, that the conduction across the steel is sufficient to keep the temperature of the coils within 0.1K of the fluid, without using complicated flow paths.

4.4. Photodesorption Experiment

In addition to the added heat load, the synchrotron radiation photons desorb gas molecules that are on the walls of the beam tube, thus increasing the gas density in the beam pipe. Previous studies showed that there were essentially no data on photon-induced gas desorption from cryogenic surfaces. New experiments were therefore necessary. A Photodesorption Task Force was set up in August 1984 and recommended a series of experiments at the vacuum ultraviolet ring of the National Synchrotron Light Source at BNL (See Appendix A for membership etc., of Task Force).

It is known from electron storage rings that the pressure rise in the presence of synchrotron radiation can be very large. The problem is solved in electron rings by designing distributed pumping into the beam tube, which removes the gas as it evolves from the wall. Eventually, the strip on the beam tube that is hit by most of the synchrotron power becomes depleted of gas, and the pressure decreases to tolerable levels. The cryogenic beam tube of the SSC is different in a number of important ways: The yield of molecules per photon, is not known. The desorbed molecules merely move to some other place on the tube, where they remain, due to the high sticking probability of the cold tube walls. They are then available to be desorbed by photons reflected with high probability from the walls. There might be desorption processes that are active at cryogenic temperatures that are absent or insignificant at room temperature.

The first results of the experiment are from an aluminum beam tube room temperature. There is more experience with aluminum beam tubes than with any other material, permitting a check on the technique and the calibrations. The experiment on the cryogenic stainless steel beam tube will start in June, 1985, and some preliminary results should be available by the end of July, 1985. The experiment will continue in order to refine the data and to test different materials, and, if necessary, different beam-tube designs.

The most important experiment is to expose the wall of the beam tube to the synchrotron light and measure the total and partial pressures as a function of exposure. This is done to measure the rate at which the clean-up occurs, in order to compare it with other experiments. A total exposure of about 6000 mA-h of circulating beam in the light source has been taken. Preliminary results from an eight-hour exposure totaling about 1000 mA-h are shown in Fig. 4.2. The graph shows the circulating beam current in the light source as a function of clock time, the total pressure normalized to the circulating beam current, and the hydrogen partial pressure normalized to the circulating current. The most puzzling result is the sudden change in the nature of the clean-up of the total pressure during each run, except for the first run, which appears as expected. Detailed interpretation must await the calibration runs. Note that the hydrogen partial pressure, which is largely determined by the beam, does not show the rising effect in any of the runs. The results agree qualitatively with the data taken at DCI, and are also in rough quantitative agreement.

The remaining program of experiments with the warm tube consists of taking beam on the room temperature aluminum tube at 10 mr average angle until the clean-up rate decreases to the point that it is no longer worth the time, exposing the other side (the "fresh side") and observing the clean-up rate,

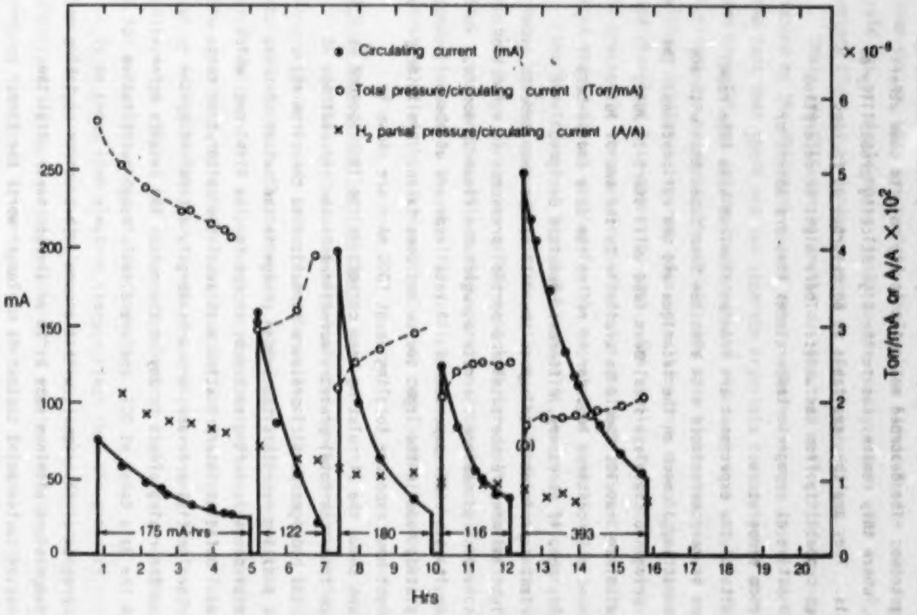

Fig. 4-2. Circulating electron beam current (lefthand scale), total pressure/beam current (righthand scale), and hydrogen partial pressure/beam current (righthand scale) vs. time in hours for synchrotron light incident at 10 mrad on a room-temperature aluminum beam tube.

taking some data at shallower angles of incidence, collimating the beam in the vertical to study the energy dependence of the desorption rate, and backfilling with boil-off liquid nitrogen, pumping down, and seeing if the clean-up rate using beam is faster than the first time. This program should be completed by mid-June, at which point the cold-beam-tube experiment can be installed.

4.5. Beam Losses, Reliability, Cost Estimates

(a) Beam losses.

Progress has been made on calculations of the beam loss, particularly the muon flux present in one interaction region from the collisions at a neighboring interaction point. The sources of muons that are considered are direct muon production, which cannot be reduced by absorptive shielding, meson decay from directly produced mesons and from mesons made in showers, and Bethe-Heitler processes. Figure 4-3 shows the muon flux as a function of the perpendicular distance from the projected direction of the outgoing beam from the neighboring interaction region. Three curves representing different distances between interaction regions of a clustered design are shown. It appears that there will be no difficulty in inserting sufficient bend between interaction regions to reduce the muon flux in the neighboring regions to much less than the cosmic ray flux.

About 30 mb of the total cross section is elastic or quasi-elastic, and most of these particles will stay within the machine acceptance for many turns before they hit the beam-tube wall. The most likely place to hit is in the quadrupoles that make up the low-beta insertions, causing a shower of particles in the close-by detector. The best way to get rid of such particles is to scrape them off somewhere else in the machine, with well-placed collimators. This is one of the inputs to the recently started design of "real lattices."

Calculations have been started at FNAL to understand the cryogenic load due to the inelastic collisions at the interaction regions. This load is significant, since each interaction region generates 1.5 kW at peak luminosity, and a large fraction of this power ends up in the cryogenic system.

Measurements have been made at the Tevatron of the amount of ionizing radiation present in the tunnel during acceleration and storage. It appears that most of this is due to local beam gas scattering, and can be used to estimate the radiation in the SSC tunnel. This radiation is important because

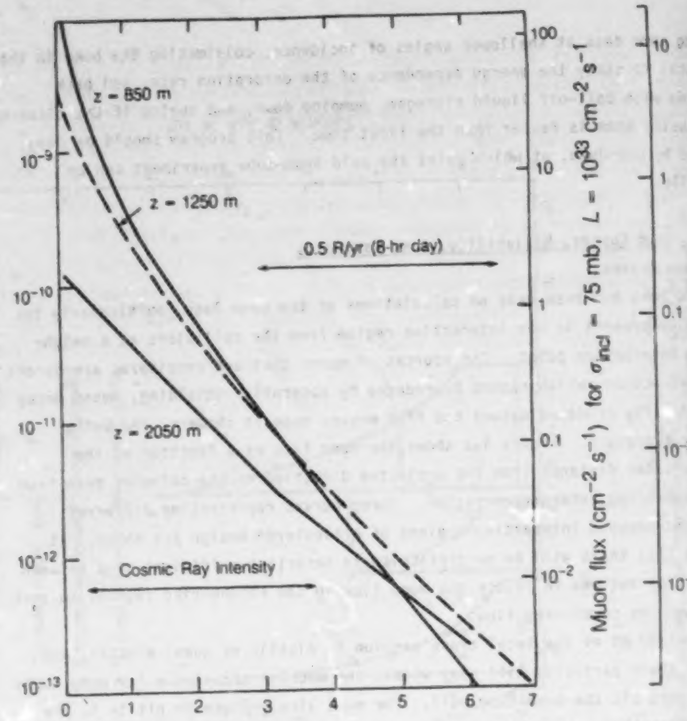

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Fig. 4-3. Muon flux for three different distances (z) between interaction regions, as a function of radial (perpendicular) distance from the axis of the muon distribution. A hadron absorbing well 80 m from the interaction point is assumed.

it affects the choices of materials used in the magnets and the lifetime of electronics in the tunnel. The preliminary results indicate that the radiation will be a significant effect; further measurements and detailed calculations are planned.

(b) Reliability.

A number of organizations, including NASA, Bell Labs, and others have techniques to perform analytical reliability studies. The issue has been discussed with people from Bell Labs, and it appears that they are willing to let the CDG use their software for this analysis. The difficult part of the work is the piece-by-piece engineering analysis of the systems and the construction of failure modes and effects models. Once such models are devised, the sensitivity of the overall system to component failure can be studied, even if the detailed component design work has not been completed. In this way, the engineering effort can be focused effectively and a plan developed for quality assurance during the construction phase of the SSC.

(c) Cost Estimates.

The cost estimates of the accelerator systems presented in the RDS are being updated to reflect new knowledge of the various designs and new design options. In the RDS, only the 6.5T design had a cost estimate for the accelerator systems. That cost estimate is being extended to include all of the magnet types now being considered. A more careful cost estimate of the testing and installation of the various magnet types is being done, and will be completed before the magnet style choice is made.

Scaling rules for cost estimates can be very useful if they are restricted to interpolations or narrow extrapolations. One of the particularly interesting scaling rules concerns the trade-off between various methods of changing the dynamic aperture of the machine. The dynamic aperture can be increased by increasing the physical coil diameter, which decreases the effects of coil errors, or by increasing the strength of the focusing by making the cell length shorter.

Figure 4-4 shows lines of constant cost per meter of effective bend for the sum of the magnet systems, correction systems and the tunnel, as a function of coil diameter and half-cell length for cosine-theta magnets (RDS type A). For a given operating magnetic field, the cost per meter of effective bend is related by a constant to the total cost. As the half-cell

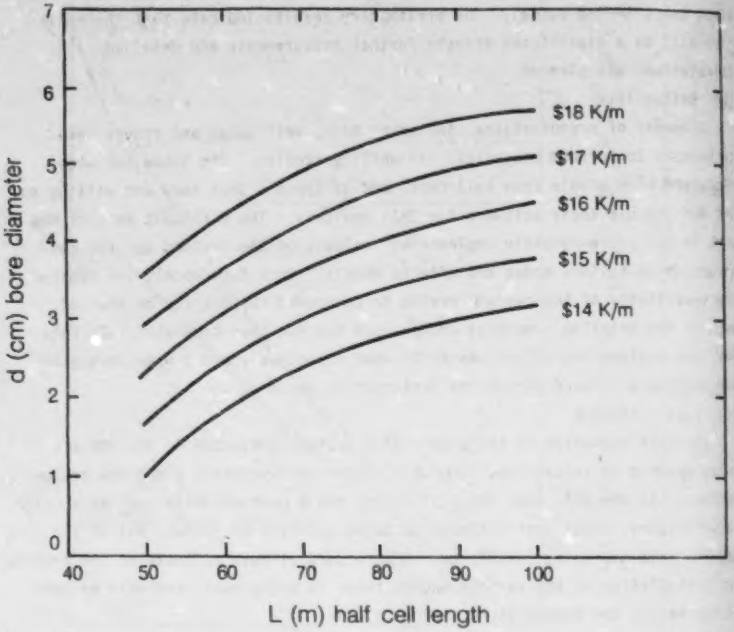

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Fig 4-4. Lines of constant cost/meter of effective bend. The quad strength is scaled as $1/\sqrt{L}$ (cost based on Ref. Design A).

gets shorter, the cost goes up because there are more quadrupoles and correction packages, and fewer bend magnets per unit length. As the coil diameter increases, the cost also increases, since at constant field the amount of superconductor increases. Whether it is better to opt for one method or the other depends on how the dynamic aperture scales with the two variables. Preliminary results indicate that for cells between 65 m and 110 m, and coils of 4 cm and 5 cm, the cost increase is not significant. For cells below 65 m, it appears that larger coils will be a cheaper option than shorter cells. This sort of scaling rule is being developed for each of the magnet designs, and the sensitivity of the rules to fluctuations in component costs is being analyzed.

4.6 Plans for the Future

(a) Systems Tests.

One of the major tasks of the ASD is to plan and manage the the magnet systems tests as described in SSC-SR-1001. As originally conceived, this would consist of two major tests, the so-called long string test, intended primarily for systems development, and a short string test, intended as a life test of the magnet system itself. The original plan has been modified since the report was submitted, adding a system test of a half-cell as early as possible. The plan is to produce one half-cell of full-length prototype magnets to be available for assembly into a string in early FY 1987. This test (Half-Cell Test) will allow early assessment of systems behavior on magnets, as well as provide a vehicle for instrumentation and cryogenic system development. The System Test Site Task Force concluded that the tests could be conducted either at FNAL or BNL.

For subsequent tests, the Half-Cell Test could be extended to become the final configuration of the Systems Development Facility, about one per cent of the SSC main ring. The Accelerated Life Test, which is basically a life test of one or two half-cells, requires a large amount of refrigeration. The decision on where to site that test will be made largely on the basis of refrigeration availability.

The Half-Cell Test effort should begin in January 1986 in order to have the facility ready for first operation at the start of FY 1987. A half-cell is expected to be available at that time, with additional prototype production during FY 1987. The System Development Facility can begin to come into being in mid-FY 1987, as the Half-Cell Test is completed. The Accelerated Life Test will be started when magnets of the final design, or close to it, are available, likely in late FY 1987.

The Systems Development Facility is expected to continue as an important test bed for engineering development and design of technical components well into the construction phase (FY 1988+), since it will be the only available complex approximating the SSC until the operation of the first sector of the main ring, scheduled for July 1990.

Another important date that impacts the Phase I R&D schedule is the projected start of operation of the first prototype refrigerator in the latter half of FY 1988.

(b) Plannad Organization of The Accelerator Systems Division.

The ASD will be organized into four groups. The groups and the tasks for which they are responsible are shown in Table 4.3. Each group will have a leader who is in long term residence at the CDG. During the early part of the R&D effort, most of the work will be done at the national laboratories, and by industrial organizations. As Phase I progresses, the CDG manpower will increase.

Table 4-3. Accelerator Systems Groups.

Headquarters
Safety
Reliability
Quality assurance
Desorption experiment
Systems tests

Mechanical
(Magnets)
Cryogenic systems
Vacuum systems
Installation
(Conventional mech.)

Electrical
Main power supplies
Quench protection
Correction elements
Control systems
(Conventional electrical)

Beams
Injection
Abort
Beam loss
Interaction regions
External beams
RF systems
Beam instruments
Operations

(c) Objectives for ASD Groups for Phase I.

The main tasks of the Headquarters Group will be to ensure a coherent set of systems designs, to design the subsystems specifically assigned to Headquarters, and to act as editor for the ASD part of written reports. Another important responsibility of the Headquarters group is to manage the photodesorption experiment and the systems tests.

The major tasks of the Mechanical Group are to design and cost the cryogenic and vacuum systems, to determine the installation method, cost, and schedule, to determine parameters that affect the conventional construction, and to ensure that the magnet design effort results in devices that meet proper standards, and fit in with the overall accelerator design. Specification of mechanical-system interfaces will be important. In addition, because the refrigerators are expected to be the most expensive single part of the accelerator systems, and because the lead time for design and construction of refrigerators is so long, it has been decided to test the first prototype refrigerator as soon after the start of construction as feasible, about nine months after Notice To Proceed. This implies that an active design, purchase, and installation-planning effort will have to be started early in Phase I.

The most important jobs for the Electrical Group are the design and cost estimates of the main power supplies and quench detection and protection of the magnets, and the same for the correction magnets. The power-supply and quench-protection designs have a considerable impact on the magnet design and development, and therefore must be vigorously pursued early in Phase I. The systems will be tested and perfected during the string tests.

A preliminary design must be done for the control systems, and estimates and specifications made for overall power needs, which are used as input to the design of the conventional construction. Despite the argument for delay in order to take advantage of the latest developments in a rapidly changing technology, the early target date for the first sector test gives rise to an equally early target date for a fully designed control system. This implies that design and prototyping, and software analysis and simulation must start fairly early in Phase I. Establishment of electrical-system interface specification will be an important objective.

The primary objective of the Beams Group in the early part of Phase I is to analyze and design the injection and beam abort systems and their integration into the whole system. This will involve a considerable amount of modeling of beam loss phenomena, particularly as they affect the operation of superconducting magnets and experimental equipment. Beam loss will also affect the tunnel design because of radiation safety requirements.

Another important early task is the development of realistic interaction regions of different types, efficiently designed for the many different experiments at the SSC. The detailed design of magnets for injection, abort, and interaction regions can probably be postponed, except for some devices that push the state of the science. Those particular devices should be designed and prototyped early, since their existence may make significant cost savings possible.

CHAPTER 5. SUPERCONDUCTING MAGNETS AND CRYOSTATS

5.1 Introduction

Our understanding of superconducting accelerator magnets has matured in the last few years; the Tevatron is operating, and HERA is under construction in Europe. Many model magnets have operated successfully and superconducting materials are much better understood. To produce a minimum cost SSC, the magnet-bore diameter must be reduced to the limits allowed by beam dynamics and long magnets must be built using mass-production techniques. It is thus essential to conduct a vigorous R&D program at an early stage. The central feature of this effort is the testing of model magnets of advanced design. This section describes the work currently being done at BNL, FNAL, LBL, TAC, and several industrial facilities. It is divided into high-field and low-field activities.

5.2 High-Field Magnets

The present high-field magnet development has been intensively pursued at LBL, BNL, and FNAL. At the beginning of FY 1984, FNAL began development of a 5 cm bore, 5T, "no iron" magnet based on NbTi cable similar to the Tevatron cable, with each of the two rings housed in separate cryostats. BNL was developing a 3.2 cm bore, ~7T magnet based on niobium tin with two coils clamped in the same cold-iron yoke to economize on iron and the number of cryostats (the 2-in-1 configuration that had been proposed for CBA). LBL was developing a 4 cm bore, 6.5T, NbTi design based on cold iron, also in a 2-in-1 configuration. In addition, BNL and LBL began a collaboration in which BNL would construct 4.5 m models of the 4 cm NbTi design, as well as the 3.2 cm Nb_3Sn design. Because of development difficulties with Nb_3Sn, the 4 cm NbTi design soon became the principal BNL/LBL focus. Collars were added for clamping the coil to simplify development and to provide a well-proven structural support. In early FY 1985, after studying cryogenic systems for cold-iron magnets, it was determined that cool-down times would be reasonable, and the 6-6.5T, cold-iron design became the main focus of FNAL as well as BNL and LBL. The three laboratories defined the 4 cm bore, 6-6.5T, NbTi, collared, cold-iron magnet as design D and began a unified development program with major responsibilities as defined in Section 2.2. Details of the development program and significant accomplishments are discussed in the following pages.

Model Magnet Construction. For any high-current-density accelerator-magnet design, building and testing models is essential to verify acceptable performance and to evaluate design details. It is especially important to verify electrical and mechanical stability (i.e., "training" behavior) and reproducibility of field quality. During the past nine months, much effort has been devotad to the design and construction of accurate tooling, the development of reliable high-performance conductors, and the evaluation of cost reduction methods. Operation of models at predicted field levels has already been demonstrated. It is planned to test six 4 cm bore, 4.5 m models in the next three months, and about twenty 1 m models of various designs. This will provide a firm data base for proceeding to design and construct prototype magnets in FY 1986.

The model magnet program can be summarized as follows:

BNL

3.2 cm, 2-in-1 Model. Testing to date has been of 3.2 cm bore, NbTi models using a CBA/Tevatron type of cable, clamped in a 2-in-1 cold-iron yoke. These models are 4.5 m long (CBA tooling and testing facilities existed for this length) and have the enlarged "dog-bone" ends designed for pre-reacted Nb_3Sn. Figure 5-1 shows a magnet during construction.

Although a larger bore diameter and a different cable design have now been proposed for the SSC, the models were completed and tested with excellent results. Four 2-in-1 magnets (eight single-hole equivalents) were built. Their performance is summarized in the training curves shown in Fig. 5-2. The lack of significant training is evident; the magnets achieve a central field exceeding that predicted. The fourth magnet used improved high-homogeneity superconductor and achieved a significantly higher field. The predicted magnetic features of the 2-in-1 design were verified.

4.0 cm Design D. The major BNL activity has been manufacturing tooling and parts for 4.0 cm design D models using the wide LBL cable, stainless steel collars fastened with keys, and a single iron yoke. Coils for six magnets have been wound and cured and the collaring process has begun. The first model was tested in June and performed remarkably well. Five more to follow in the next three months. These magnets will have full-length sextupole correction coils wound with a single layer of 0.023 cm diameter superconducting wire and attached to the o.d. of the bore tube.

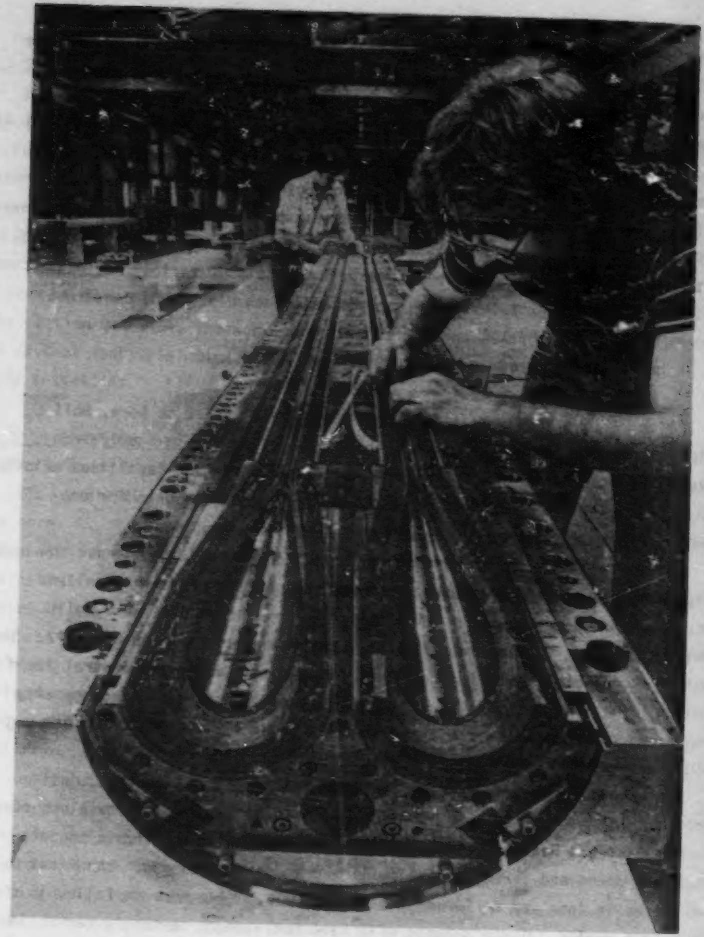

Fig. 5-1. Lower half of two-in-one high field magnet during assembly.

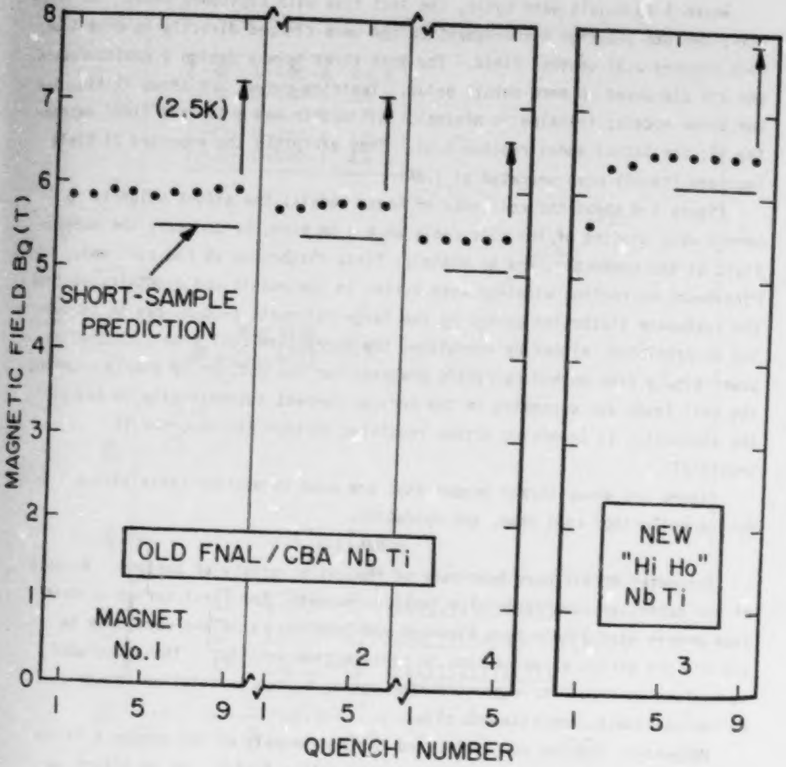

Fig. 5-2. Magnetic field at quench (4.5K) for four 2-in-1, 4.5 m BNL "A" high-field dipole magnet models with 3.2 cm aperture.

LBL

Seven 4 cm models were built, the last five with keystoned cable. Of these five, two had a design A configuration and were clamped directly in cold iron; both reached 6.5T central field. The last three have a design D configuration and are discussed in more detail below. Training curves are shown in Fig. 5-3 for these models; training is minimal. All models had a central field exceeding 6T; the latest model reached 6.5T. They exhibited the expected 2T field increase (to 8T) when operated at 1.8K.

Figure 5-4 shows the coil ends of these models; the slight bulge is to permit easy winding of the wide cable on a 4 cm bore, to decrease the maximum field at the conductor, and to minimize field distortion at the coil ends. Wire-wound correction windings were tested in the models and demonstrated that the sextupole distortion caused by the large filaments (~20μm) can be cancelled as predicted, either by energizing the correction coil from a controlled power supply (the method currently proposed for the SSC) or by simply shorting the coil leads and depending on the induced current automatically to cancel the distortion (a promising method requiring further R&D to prove it practical).

Figure 5-5 shows strain gauges that are used to monitor cable stress during collaring, cool down, and operation.

FNAL

One-meter models have been made at FNAL of a variety of designs. Because of the extensive experience with Tevatron magnets, the first series of thirteen models used 3-inch bore diameter and Tevatron cable and were made to explore the effect of variations in construction details. These included variations in copper-to-superconductor ratio, helium ventilation channels, collar stiffness, and filament size.

Meanwhile, tooling was fabricated for 5 cm models of the design B "iron-free" magnet that required a new cable and collar design. In an effort to reduce the cost, an epoxy-free ("dry wound") fabrication method was developed wherein the coils are wound and collared in a single step. A collapsible mandrel is used to facilitate winding and collaring. Figure 5-6 shows collars being assembled on one of these models. Six models have been wound and cryogenic testing began in June.

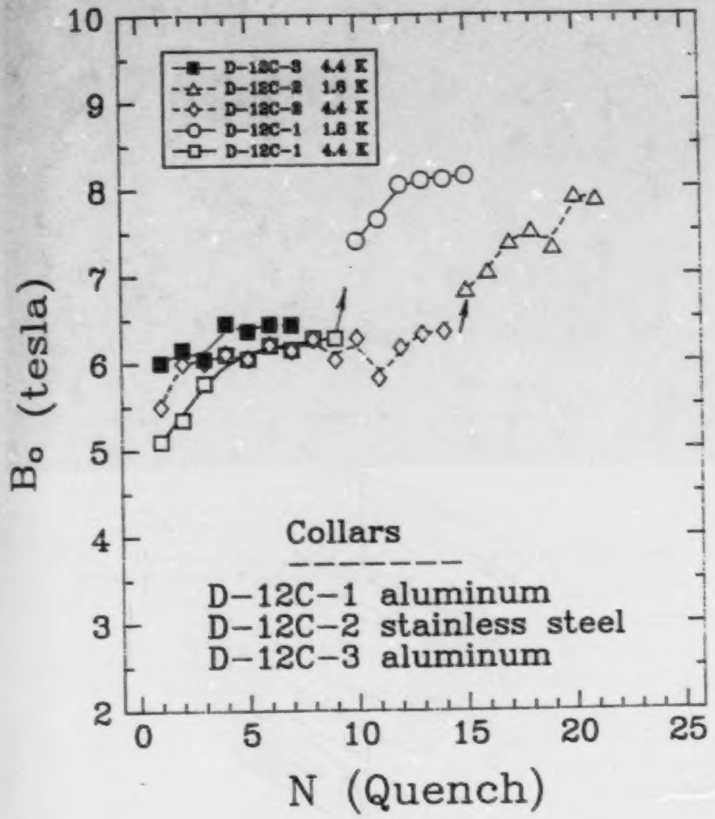

Fig. 5-3. Training for LBL 1 m dipole models, 4.0 cm bore diameter.

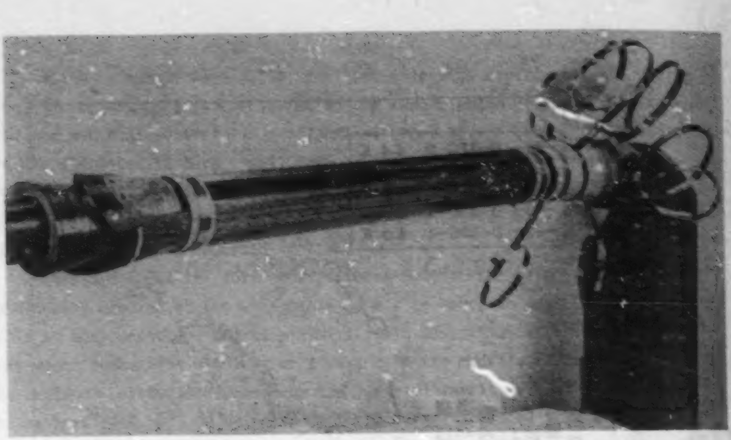

Fig. 5-4. Flared coil-end design for high-field magnets.

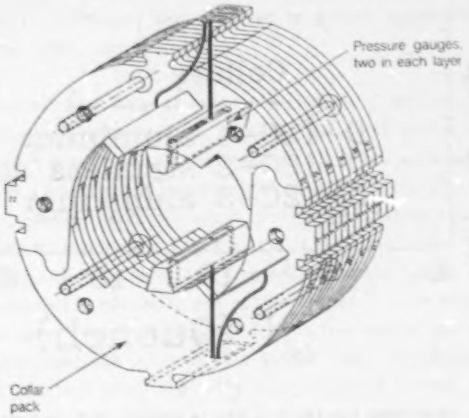
Pressure gauges, two in each layer
Collar pack

Fig. 5-5. Illustration showing pressure gauges insulated in collars to measure winding pressure during assembly and operation of 4 cm LBL models.

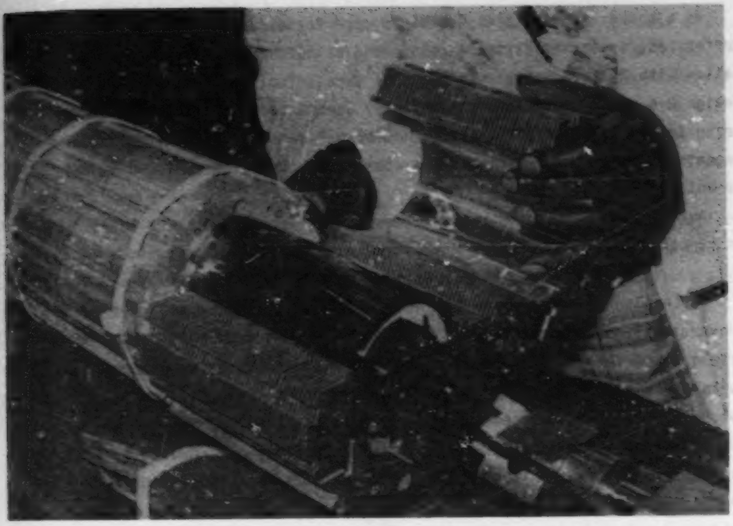

Fig. 5-6. Aluminum collars being applied to a one-meter, high-field, dry-wound (epoxy free) coil assembly.

As a backup construction technique, and for direct comparison of the two approaches, several models are being made using the well-proven Doubler insulation with B-stage epoxy and Fiberglas tape. Tooling has been made to build design D 4 cm bore models using the "dry wound" technique and fabrication will begin in June. It is anticipated that by October, 1985, ten 5 cm design B magnets (5 "dry" and 5 with B-stage epoxy) and five 4 cm design D magnets will be built.

Auxiliary R&D Programs. Several essential developments are being done in support of the magnet program and are summarized below:

Distributed Correction Coils

As an alternative to fine-filament superconductors, we are developing a conventional corrector driven by a separate power supply. Although initial models have wire-wound coils, a mass-production technique to produce low cost coils is being developed at BNL in collaboration with industry. Using technology originally developed for the electronics industry, small diameter (0.008 in.) superconducting wire is being accurately attached to a Mylar base to form single-layer coils. The Mylar, with coils attached, is then wrapped around the bore tube. Wire can be laid down at 5m/min, and the coil can be full length (16 m). Several 2 ft-long sample windings have been produced.

Field-Measurement Mole

Significant economies can be realized if magnetic fields can be conveniently and accurately measured in long, small-diameter magnets. Using existing technology for miniaturized motors, gravity sensors, telemetry, etc., a probe with a rotating coil assembly and a diameter of less than one inch is under development at BNL. The first model has been built and a more advanced model is under construction. Initially a tether will pull the probe through the bore tube, but a self-propelled unit is being designed.

5.3 Low-Field Magnets

Development of a 3T dipole magnet has been pursued at the Texas Accelerator Center (TAC), with support from several high-energy physics laboratories and with extensive industry collaboration. Fig. 5-7 shows the present design in the 2-in-1 configuration. It is extremely compact and, because of the low field, requires less superconductor than the high-field design. Because of the large accelerator circumference (165 Km) required at the 3T field level, the program is aimed at developing very long magnets to minimize the number of units requiring in-tunnel connections. It is hoped that 115 m-long units can be fabricated consisting of three 35 m dipoles, a 4.7 m quadrupole, and with correction coils, cryogenic equipment, and expansion joints contained in the remaining 5.3 m.

Since TAC started work about one year ago (March 1984), considerable effort has been devoted to assembling shop facilities, cryogenic facilities, magnet instrumentation, and a staff. The main effort at TAC has been to complete the dipole design and to fabricate models.

To maintain field uniformity up to 3T, the coil is divided into two circuits that are driven by separate, coordinated power supplies, and a one turn correction winding, driven by a third power supply. Fig. 5-8 shows the magnitude of current in the three windings as central field varies; the relative currents must be closely controlled to maintain field uniformity over the entire field range. TAC has assembled three 1 m single-channel magnets, one 1 m 2-channel magnet, and one 7 m 2-channel magnet. Two 1-channel models are shown in Fig. 5-9. An end of the 7 m model with the two elliptical bore tubes protruding is shown in Fig. 5-10. In addition, General Dynamics-Convair Division, has assembled a 1 m 1-channel magnet and has contracted to assemble three 28 m models at their San Diego facility using parts supplied by TAC, and to ship them to TAC for testing. These models will be complete with cryostats. Tooling is built (see Fig. 5-11); the first magnet is under construction and is expected to be shipped in late September.

Cable for the low-field magnet contains more copper than the high-field cable, to limit the heating rate in the event of a quench. The ratio of copper to superconductor is 4.0, obtained by wrapping 24 0.7 mm-diameter strands around a rectangular copper strip, soldering the strands in place, and rolling to size. The strand was chosen to be idential to the strand used for the design D inner cable, but drawn to 0.1 mm smaller diameter. Thus there is interchangability between conductor procurements. A benefit of the large amount of copper appears to be good electrical stability; the models reach design field with little or no training. Quench propagation velocities are close to predicted values.

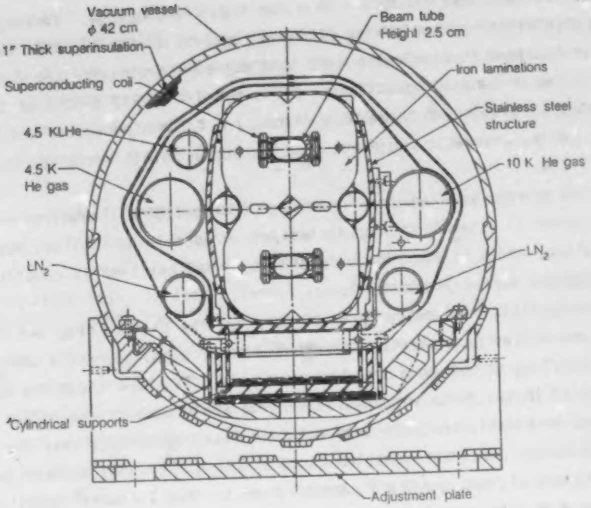
Vacuum vessel
ϕ 42 cm
1" Thick superinsulation
Superconducting coil
4.5 KLHe
4.5 K
He gas
LN₂
Cylindrical supports
Beam tube
Height 2.5 cm
Iron laminations
Stainless steel
structure
10 K He gas
LN₂
Adjustment plate

Fig. 5-7. Current version of the 2-in-1, low-field superferric magnet design.

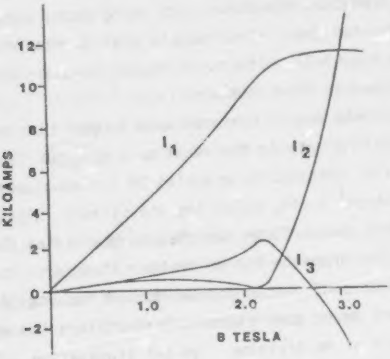

Fig. 5-8. The three independent currents as a function of magnetic field.

Fig. 5-9. One meter models of low-field superferric magnet.

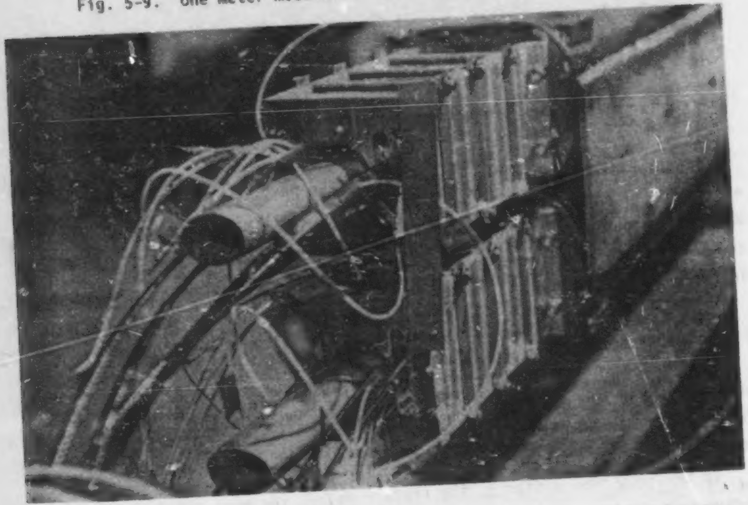

Fig. 5-10. End view of 7 m model of low-field superferric two-in-one magnet.

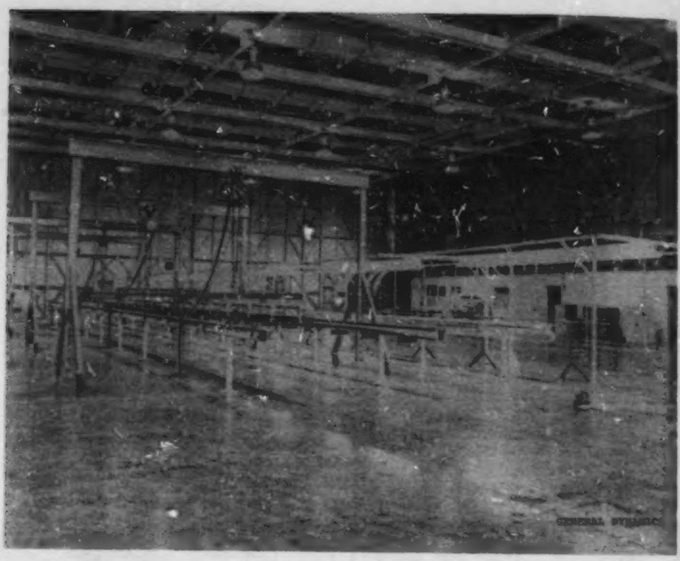

Fig. 5-11. Tooling for production of 28 meter superferric model at General Dynamics.

Considerable effort will be devoted in the next few months to experimental evaluation of magnet field uniformity. Field quality measurements have been encouraging but not yet definitive. Measurement facilities are being improved and several additional models of both 1 m and 7 m length will be built at TAC in the next few months.

5.4 Cryostat Development

Cryostat development work to date has largely been done at FNAL and has been focused on the original iron-free design. However, the techniques developed can be adapted to other magnet types. The following three major projects were done at FNAL.

In the iron-free design B, the field envelops the heat shields and creates forces between the coil assembly and the iron cryostat wall. A 20 ft-long model was constructed to evaluate experimentally the effect of eddy currents on heat shield deformation during quenching and to measure the interaction between coil and cryostat wall. A Tevatron coil was installed. The test sequence evaluated the response of cryostat components to magnet coil quenches at various levels of current. The mechanical and thermal response of the radiation shield was measured; the coil was then deliberately mounted slightly off center and retested, with results that agreed with predictions.

Another model was constructed to evaluate heat leak into a design B cryostat, shown in cross section in Fig. 5-12, with a dummy magnet to simulate the correct size and mass. End terminations, shown schematically in Fig. 5-13, were constructed to permit determination of the very small heat leaks by measuring the boil-off of helium and nitrogen. Figure 5-14 shows this cryostat under construction with the multilayer insulation blanket being applied. The heat leaks to 4.5K, 10K, and 80K temperature components was measured. The results are discussed in Section 4.2.

A small Dewar facility illustrated in Fig. 5-15 was constructed to evaluate a variety of low-heat-leak magnet-support designs and also to provide preliminary data on multilayer insulation schemes (MLI). Measurements on a post type of support in this Dewar were completed. The measurements included heat leak into the intermediate temperature shield operated at temperatures other than 10K, i.e., 20K, 30K and 40K. The results of the measurements agreed well with those predicted. Measurements were also made with the connection to the intermediate temperature shield removed and with the shield operating at 10K, 20K, 30K and 40K. This Dewar is now being converted to evaluate multilayer insulation systems and their application techniques. The initial MLI system to be evaluated is reflective polyester film with a Fiberglas mat spacer. A program is being developed to study the effects of various insulation techniques and suspension systems.

In addition to experimental work, several preliminary design efforts were carried out to evaluate candidates for a type D cryostat, and a Cryostat Task Force was established. This work is still in progress. A design criteria document was developed to guide design efforts on type D cryostats. A rather complete design utilizing tension supports, shown in Fig. 5-16, was made for the purpose of cost analysis. A design based on compression-member supports was done by General Dynamics-Convair, under contract to LBL, and creep-testing

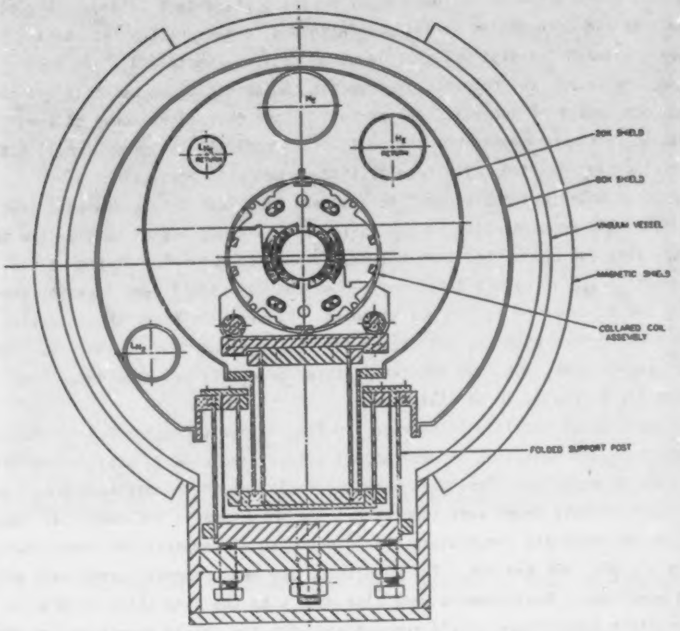
He
LHe RETURN
He RETURN
20K SHIELD
80K SHIELD
VACUUM VESSEL
MAGNETIC SHIELD
COLLARED COIL ASSEMBLY
FOLDED SUPPORT POST

Fig. 5-12. Modified Design B magnet assembly with folded post arrangement.

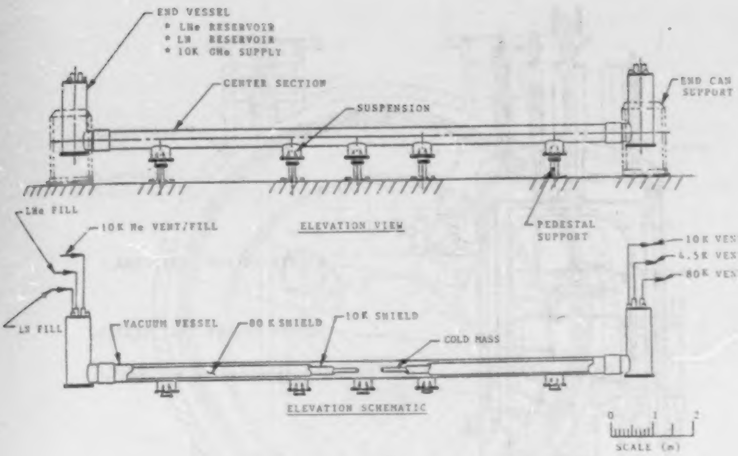
END VESSEL
* LHe RESERVOIR
* LN RESERVOIR
* 10K GHe SUPPLY
CENTER SECTION
SUSPENSION
END CAN SUPPORT
PEDESTAL SUPPORT
ELEVATION VIEW
LHe FILL
10K He VENT/FILL
LN FILL
VACUUM VESSEL
80 K SHIELD
10K SHIELD
COLD MASS
10K VENT
4.5K VENT
80K VENT
ELEVATION SCHEMATIC
0
1
2
SCALE (m)

Fig. 5-13. 12 m Heat Leak Measurement Model

Fig. 5-14. Final installation of the multilayer insulation blankets on the Magnetic Effects Model.

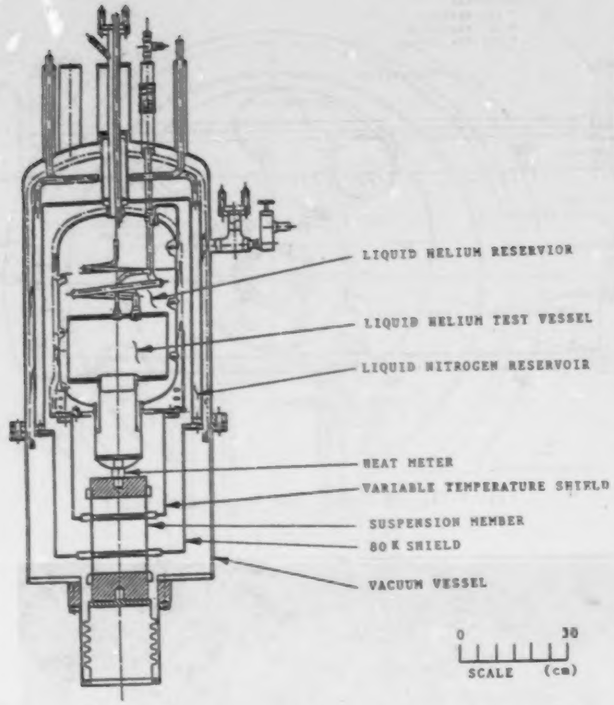
LIQUID HELIUM RESERVIOR
LIQUID HELIUM TEST VESSEL
LIQUID NITROGEN RESERVOIR
HEAT METER
VARIABLE TEMPERATURE SHIELD
SUSPENSION MEMBER
80 K SHIELD
VACUUM VESSEL
0
30
SCALE (cm)

Fig. 5-15. Suspension Heat Leak Measurement Dewar

of a model compressive strut was initiated by LBL at the NBS-Boulder laboratories. An adaption of the HERA cryostat design was proposed by BNL. During June and July, a design will be selected for further evaluation and for use with the long (12-16 m) magnet models planned for FY 1986.

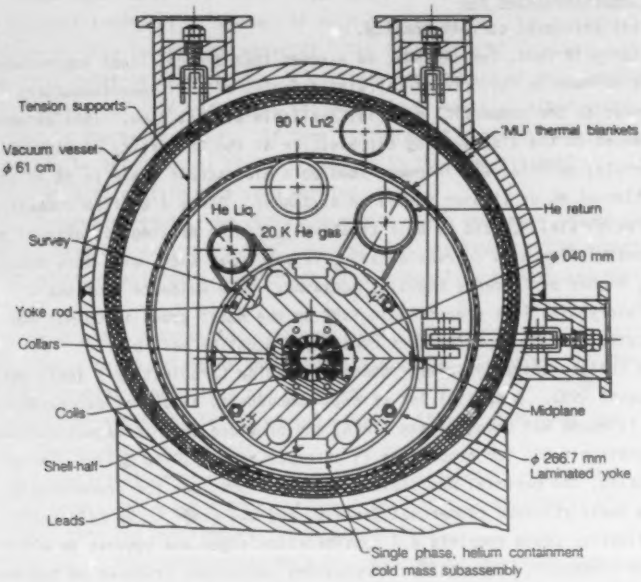
Tension supports
Vacuum vessel ϕ 61 cm
80 K Ln2
'MLI' thermal blankets
He return
He Liq.
20 K He gas
Survey
ϕ 040 mm
Yoke rod
Collars
Coils
Midplane
Shell-half
ϕ 266.7 mm Laminated yoke
Leads
Single phase, helium containment cold mass subassembly

Fig. 5-16. The current concept of the FNAL cryostat for the type D SSC magnet.

5.5 Superconductor R&D

(a) Increased current density.

Early in 1984, for the RDS, we assumed that a significant improvement might be made in the current-carrying capacity of NbTi superconductors compared to the commercial material available at that time. This assumption was based on the discovery by Larbalestier at the University of Wisconsin that commercial material was inhomogeneous on a microscopic scale (± 5% in atomic fraction of Nb or Ti over 50-100 μm distance). Since a uniform concentration of precipitates, caused by heat treatment and wire drawing, is assumed to be responsible for high current density, it was hoped that, with more homogeneous NbTi, higher performance might be achieved. Some evidence from small laboratory-size lots (reported in 1982 by the Baoji group in China) had indicated that high-performance conductors might be possible.

A collaborative experiment aimed at testing Larbalestier's ideas was begun in August 1983. A special lot of high-homogeneity alloy was purchased by LBL from Teledyne Wah Chang Albany (TWCA) and provided to Intermagnetics General Corporation (IGC) for processing in an experimental 10-in billet. After extrusion, the material was divided into two lots, one for processing by IGC, using their standard commercial process, and the other to be held until Larbalestier could complete a J_c-optimization study and suggest an alternative treatment. Conventional processing techniques produced an improved J_c (about 2300 A/mm^2 compared with about 2000 A/mm^2 for the best Tevatron/CBA material). This result was verified on two additional billets procured by LBL. The remainder of the experimental billet, processed with a new heat-treatment schedule, resulted in significantly improved J_c values (from 2365 A/mm^2 to 2645A/mm^2 for the 0.025 in. diameter strand). Based on these results, LBL ordered two additional billets and FNAL ordered five billets. This material was delivered in January, 1985. The J_c values in all cases exceeded our specification values of 2400 A/mm^2.

The final order for material for design D dipoles was placed by LBL in November 1985 after the competitive bidding was won by IGC. IGC delivered 820 pounds of inner-layer strand and 830 pounds of outer-layer strand in April, 1985. The J_c (5T, 4.2K) values are 2509 A/mm^2 for the inner and 2719

A/mm^2 for outer-layer material. Outer-layer material, properly processed with the new heat treatment (3 periods of 40 h each at 375°C), has a significantly higher J_c than inner-layer material. The FNAL material is equivalent to the superior outer-layer material. A possible explanation of this behavior is that the additional cold working of the outer-layer material after extrusion is beneficial in improving the J_c. If true, this result suggests that it may be possible to get somewhat higher J_c values in the fine-filament conductors that also contain more cold working.

Another favorable result from these procurements has been much longer piece lengths (less breakage during drawing) compared with the Tevatron/CBA experience, which greatly facilitates cabling and also simplifies testing and quality control.

There now exists a substantial data base from these production-size billets (15 billets for a total weight of approximately 5000 lbs, including the FNAL billets), and several conclusions can be drawn:

(i) The interim SSC specification value for J_c (5T) of 2400 A/mm^2 can be met in industrial-scale production;

(ii) The specification of high-homogeneity NbTi appears to reduce the spread in J_c values (although a more stringent test of this hypothesis will come when more than one manufacturer is in production);

(iii) The use of high-homogeneity NbTi has resulted in extremely long piece lengths.

Improved heat-treatment schedules are still being investigated. There are indications that further improvements in J_c of production material (perhaps to 3000 A/mm^2) might be possible. For design D, a 12.5% increase of J_c (5T, 4.2K), from 2400 A/mm^2 to 2700 A/mm^2 would result in an 8% savings in total cable cost (about $25 M). Alternatively, if the magnet is operated at 4.2% higher field with the same cable, the accelerator size could be reduced (implying a cost reduction of about $40M). Cost savings proportional to the reduced amount of superconductor used will accrue to the low-field design, too.

(b) Fine Filament Superconductor.

The SSC magnets must have a very uniform field over a range from 5-10% of full to full field. Eddy currents that do not decay are induced in superconducting filaments when the field is changed. These persistent currents cause a distortion in the field that, for a given conductor, is roughly proportional to filament size. For example, Fig. 5-17 shows the expected distortion in a 4 cm type D model with various filament sizes. Measurements

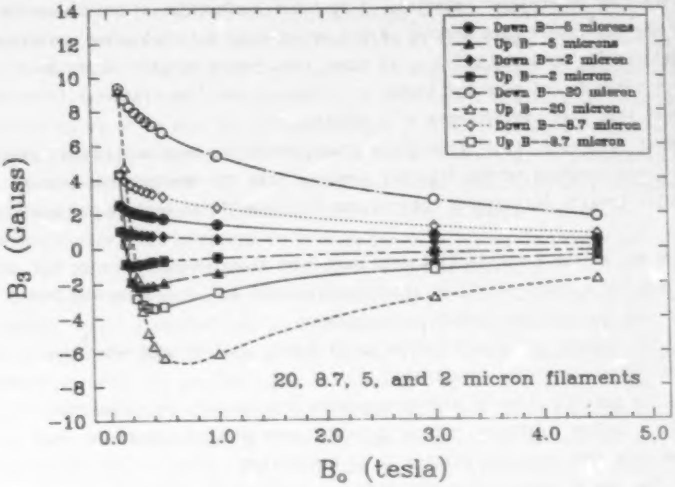

Fig. 5-17. Examples of prediction of sextupole component of field distortion caused by induced persistent currents, for 2, 5, 8.7, and 20 μm diameter filaments.

agree with these predictions. (The effect is much smaller in the 3T, type C configuration) This distortion can be corrected by a small correction coil wound on the o.d. of the bore tube. However, if filaments of 2-3 μm can be used, this correction coil is not needed. Therefore, vigorous efforts are being devoted to the development of fine-filament NbTi. The technical and economic problems of very fine filaments can be summarized as follows:

Conventional production of NbTi superconductor consists of a hot extrusion (500-600°C) of NbTi rods in a copper matrix. During this extrusion and the prior heating of the billet, a layer of titanium-copper intermetallic compound, 1-2 μm thick, can form around the filaments. This brittle intermetallic layer does not co-reduce and thus can become equal to the filament diameter at final wire size. This results in extensive filament breakage and sometimes strand breakage. The problem can be eliminated by enclosing the NbTi rods at extrusion size in a barrier material, such as Nb, which prevents the formation of the intermetallic titanium-copper. The barrier need only be 0.1 to 0.2 mm thick, and will be reduced to an insignificant fraction of the filament cross section at final filament size.

Another problem can arise from the introduction of foreign particles during the billet preparation. Any "dirt" consisting of micron-size particles or any inclusions of this size in the NbTi rods or the copper components can result in filament breakage at the final wire size. This type of problem is insidious, since processing may proceed successfully until the final wire size is approached. Also, the size of inclusion that is tolerable depends upon the desired filament size, e.g., a one-micron-diameter inclusion is acceptable for a 20 micron filament, but not for a 2 micron filament. This problem can be eliminated by careful selection of raw materials and by clean-room practice in billet assembly.

When a large number of rods are stacked in a billet, as is necessary to achieve fine filaments, voids may be present that can lead to non-uniform reduction during extrusion and drawing. This can lead to filament breakage and reduced performance. The problem can be eliminated by compacting the billet before extrusion.

When these potential problems are eliminated by proper processing and quality control, there is no metallurgical reason why a J_c of greater than 2400 A/mm^2 cannot be achieved in filaments less than 2.0 μm in diameter. In fact, the increased total reduction in area of the NbTi filaments may mean that it is possible to introduce more heat treatment cold work cycles and hence raise the value of J_c further.

When these potential problems and the proposed solutions were discussed with the superconducting material manufacturers, several manufacturers responded with proposals to investigate the production of high J_c, fine-filament NbTi using several different methods, and contracts were placed in October 1984 to deliver material for determination of J_c and construction of model magnets, and for an economic analysis of the fabrication method. The feasibility of utilizing hydrostatic extrusion to produce fine-filament

NbTi is also being explored. Figure 5-18 shows some very encouraging preliminary data from several samples.

To have filaments as small as 2μm in practical strand sizes, the finished strand must have as many as 50,000 filaments. This requires some form of rebundling during wire manufacture or during cabling (cable of cables). A preliminary estimate of the costs for fine-filament NbTi produced by these alternative methods has been made. A rough estimate of the costs of fine-filament NbTi indicate a 15 to 30% premium compared with the costs of conventional 20 μm filament material. More accurate cost information will be obtained at the end of the R&D work (September 1985).

(c) Cable Development.

Cable made from round strands and flattened to approximately 90% compaction is used for nearly all accelerator magnets because it is easy to wind, can be made in a large variety of shapes and sizes, and can have low eddy-current losses when the field changes. The SSC presents more stringent cable requirements than the Fermilab Doubler because of field-uniformity requirements and the need to use a different cable in the inner and outer layers of the winding in order to minimize the cost of superconductor.

The techniques and specifications for manufacturing the type D cable for the SSC models were developed at the LBL cable facility (shown in Fig. 5-19) and utilized by New England Electric Wire Company (NEEW) to produce cable for the type D models. 20,000 feet of cable for type D magnets have been produced, about half at NEEW and half at LBL for type D model construction at BNL, FNAL, and LBL.

Improvements have included a new mandrel design to reduce friction and "crossovers," more accurate tension control, and a new Turkshead roller system to maintain accurate cable thickness. In addition, specifications for cable dimensions, and strand pitch, and twist, etc., were developed at the laboratory facility. Continuing work is directed at closer control of cable dimensions, improvement of winding ease, and minimizing superconductor damage caused by wire deformation.

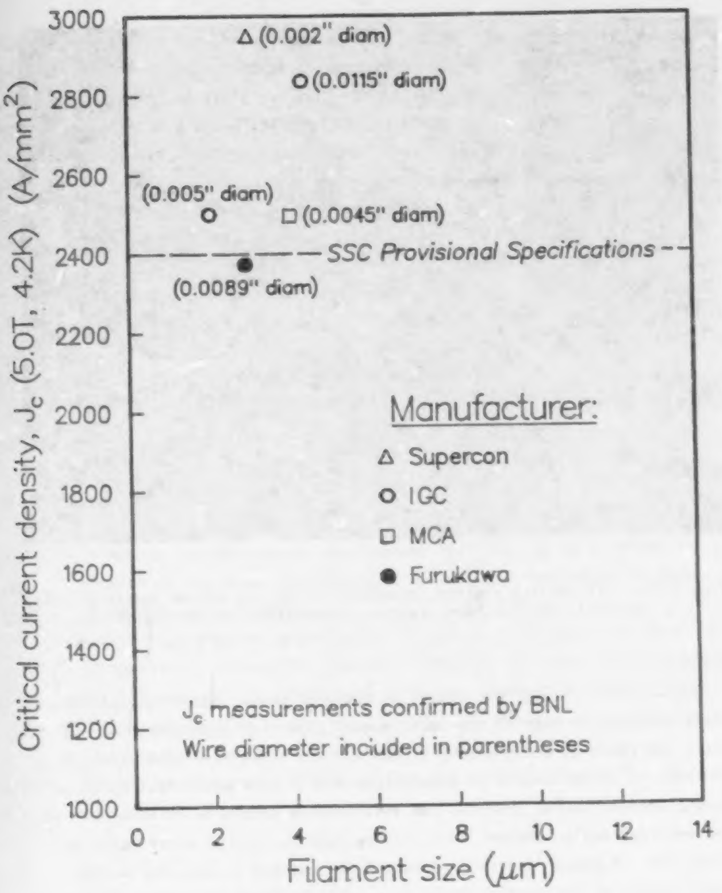

Fig. 5-18. Recent fine-filament NbTi results on maximum J_c at 5T, 4.2K.

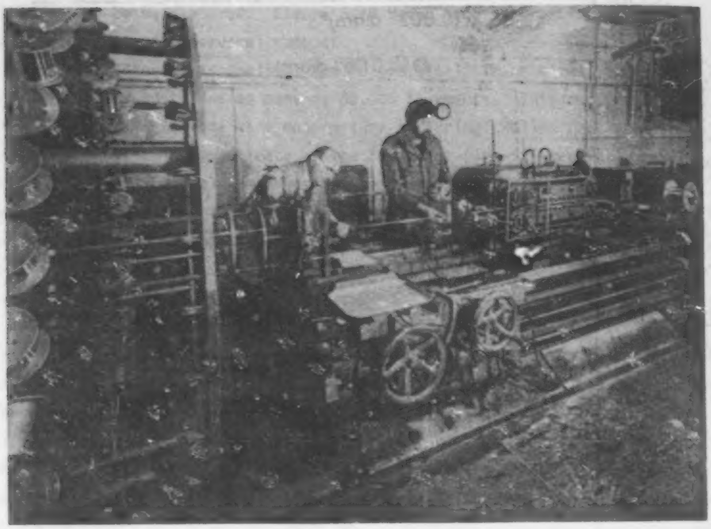

Fig. 5-19. LBL cabling machine, planetary drive for strand spools at left, mandrel and Turkshead, center, caterpillar tensioning device, right.

5.6 Plans

During the current, pre-selection stage of magnet modeling, laboratory-style tooling for each of the basic magnet types has been assembled and used. Given the rates at which models of the various types have been produced in FY 1985, it is reasonable to expect that a half cell equivalent length of full length dipoles can be produced and individually tested in FY 1986, even with the expected design changes that will be made by the CDG after basic type selection. Manpower and shop resources now engaged in parallel magnet developments of the various basic types will be freed to enhance dipole production or to begin work on quadrupole and/or spool model development. Each of the laboratories now participating in magnet R&D will be invited to take up one or more of these areas. As shown in Fig. 9-3, p. 113, ten quad models and four R&D spools represent a reasonable expectation based on historical performance records for these items at FNAL and BNL, where specialty quadrupoles have been rapidly produced for various purposes in the past several years. Achievement of technical performance verification for the selected magnet type appears a practical goal for FY 1986.

Looking forward, however, it is clear that a beginning in 1986 of significant industrial involvement in magnet prototyping and redesign for efficient production would be highly desirable. This early industrial participation would have several advantages: It would draw in industrial experience for the benefit of the first prototypes; it would lead to firmer cost estimates for magnet production; and it would start the process of discovering those firms truly competent to participate in the SSC. Further, if several parallel contracts could be let, a well-defined vehicle for U.S. and foreign industrial participation in the SSC would be created. In the schedule for FY 1987 and FY 1988 of Fig. 9-3 it has been anticipated that industry will be prepared, through FY 1986 activities, to begin actual prototype production in FY 1987 that will contribute to those magnets included in the FY 1987 magnet-system tests.

Based on the anticipated modeling and design program for FY 1986, the quadrupoles needed for the Systems Development Facility can be produced in FY 1987, as well as the spool pieces needed to complete the cells and couple them to the refrigeration system.

A number of high-gradient quadrupoles are needed to produce the tight focus at the high-luminosity interaction regions. With the improved superconductor now available it may well be possible to construct quadrupoles which exceed the performance anticipated in the RDS. If so, this increased gradient may be parlayed into improved performance in terms of event duty factor or cost savings through lowered beam intensity. Thus the program planned for FY 1987 includes significant R&D development of these important components.

CHAPTER 6. INJECTOR

6.1 Plans for FY 1986 and Beyond

An important effort will begin in FY 1986 on development of an optimum injection system for the SSC collider ring. The desired parameters of the injected beam will be established in concert with the determination of the collider ring lattice and magnet characteristics. The injection system is currently visualized as a sequence of three accelerators: a 1-Gev linac, a rapid-cycling low-energy booster synchrotron (70 GeV) with conventional magnets, and a high-energy booster with superconducting magnets and an energy of 1 TeV. Further studies will determine the optimum energy and beam characteristics of each injector accelerator system. Work will begin on the overall lattice system for both booster accelerators and the required magnet parameters. In particular, for the high-energy booster a program will be inaugurated to provide prototype models of the superconducting magnet designs.

While the parameters of the injected beam will be matched to the requirements of the main storage ring, it is important that the overall injection system of cascaded accelerators be designed for maximum reliability in operations. This will require careful consideration of the design and component specifications for the many subsystems of each of the injector accelerators.

Other considerations for the injector complex will include an examination of the the use of the proton beam from the high-energy booster as a source of test particles for detector development and calibration. Since the collider will require its beams for only an hour a day or so, the injector could be used for test purposes, provided an economical mode of operation is found.

CHAPTER 7. DETECTORS

7.1 Introduction to the problem

There is strong agreement in the U.S. high-energy physics community that the SSC detectors will present formidable technological challenges. It is also clear that detector requirements will have an impact on the actual accelerator design and the conventional construction in the interaction regions. Some of these questions have been addressed in a preliminary way in the DPF-sponsored Summer Study at Snowmass in 1984. That study reinforced the general feeling that the detector R&D should not be postponed for very long if efficient SSC detectors are to be available at the time of the SSC turn-on.

As a historical guideline for the SSC detector time scale, one could consider the LEP example. The formal approval for four 4π detectors was given by the Director in the summer of 1982, some six and a half years before the actual scheduled turn-on of the LEP itself. The initial collaborations for these proposals actually started about two years earlier. This may be an extreme example. Both the UA1 and UA2 detectors were conceived, designed, and built on a time scale about a factor of two shorter than the LEP detectors. However, because of some rather difficult technical challenges that will confront the SSC detectors, one could argue that their optimum time schedule should be closer to that used for the LEP detectors.

There are also administrative questions connected with the problem of SSC detector R&D. Major efforts need to be mounted in some areas of detector R&D in order that the outstanding problems be solved. These efforts will require substantial resources in terms of money, manpower, and test-beam time. Some coordination of these efforts thus appears warranted to assure that the use of these resources is optimized. Opinions have been expressed that the detector R&D effort needs to go beyond the traditional university group participation and CDG might have to play a significant role in this area.

To explore these technical and administrative questions, a Detector R&D Task Force has been appointed by the CDG under the chairmanship of Professor M. Gilchriese of Cornell University. The details of the charge, composition, and meetings of this Task Force are listed in Appendix A. The preliminary report of this Task Force was prepared and presented to HEPAP at its May 24 working group meeting at SLAC. The description of the required SSC detector program is largely based on this report.

The specific technical challenges that will be faced by the detectors at the SSC are attributable to the anticipated high luminosity, high energy, and large scale of the detectors and to severe physics-motivated requirements. These problems, and thus the required R&D, can be broken down into several different areas, i.e., tracking devices, calorimetry, electronics, data acquisition, triggering, computing, muon detection, particle identification, and large superconducting magnets. All of those, except the last two, are discussed in the Task Force preliminary report.

Several specific areas requiring generic (i.e., independent of specific detector design) R&D have been identified. Understanding potential radiation damage to the tracking devices, local electronics and calorimetric material, and finding ways to prevent or cure it are crucial to high luminosity operation. The implementation of triggering to achieve 10^8 to 1 reduction in data rate is another important problem. Data-acquisition techniques and the best way to implement large-scale computing requirements need serious study. Because the events are expected to be complex and frequently overlapping in time, detailed Monte Carlo studies need to be made to understand pattern-recognition problems, required parameters of tracking devices, and potential faking of rare events. The high energy of the SSC imposes serious problems connected with muon tracking, questions of how deep calorimeters need to be, and stringent requirements on tracking devices if momenta are to be measured via sagitta determination.

The above is by no means an exclusive list. It exemplifies some of the problems that require investigation and indicates the need for an early start on detector R&D problems.

7.2 Time Scale and Required Resources

It is proposed that well-organized, focussed workshops or study groups could be productive almost immediately. The goal of this phase would be to achieve a better understanding of the problems and to make recommendations for specific work. A reasonable time scale to achieve some conclusions would be the 1986 Snowmass Summer Study. For these workshops to be productive, significant participation by experts in the area of study is necessary. Since these experts might have to come from abroad or from industry, they may require travel support. Most of these problems will need extensive additional

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Monte Carlo work to aid in designing the prototypes and understanding experimental results.

The results of these workshops and study groups would lead to specific hardware and software R&D that should commence at the beginning of FY 1987. The generic detector R&D probably should not be extended much longer than 1-2 years. After that it would be appropriate to focus on more specific problems and subsequently begin overall detector design. The time scale for large detector construction for the SSC is estimated to be 7±2 years, the error being at least partially due to potential uncertainties in the funding profile.

A crude and preliminary cost estimate for the generic detector R&D in FY 1987 and beyond is given in Table 7.1 In addition, an estimate of about $250K/year in travel funds was deemed necessary starting in FY 1986 to support the required travel budget for invited workshop participants.

These cost estimates do not allow for any test-beam support or additional test-beam construction. The availability of test-beams is rapidly becoming a crucial worldwide problem even without the SSC requirements. It appears that additional test beams will have to be built at Fermilab to accommodate the future requirements. This will have fiscal implications for capital equipment funds, beam-maintenance personnel, and possibly additional running time. Later on, high-energy test beams will be needed both from the SSC injector and perhaps from the SSC itself.

7.3 Organization and Plans

The Detector R&D Task Force has recommended that the CDG play
ficant role in organizing and managing the detector R&D effort.
arguments behind this recommendation are continuity of effor
for workshop activities), ability to influence the budget
time advocate for detector R&D and for a source of inf
R&D needs. In discharging their detector R&D respo
be advised by a Detector R&D Advisory Committee
an evolution of the Task Force.

The Detector R&D Task Force is at prese
broader participation from the high-energy phy
as well as several foreign members. The foreign
Task Force the know-how about the detector R&D in th

d Original

Table 7-1

Preliminary Cost Estimate for Generic Detector R&D Starting in FY 1987*

	K$/year
Radiation damage to wire chambers	250
Radiation damage to silicon microstrips	100
Custom IC design capability	500
Fast response calorimetry	200
Radiation damage to sampling media	100
Extension of calorimeter prototype tests to high λ, E	500
New sampling media for calorimeters BaF$_2$, silicon, warm liquids, glass	500
Scintillating glass fiber development	250
Semiconductor device/detector R&D	450
Muon ID tests at high energy	200
Better hadron shower codes	50
Vectorization of some codes	50
Incremental support for multiprocessor projects - offline and triggering - test beds for SSC	1000
Networking - worldwide: must be improved for SSC	~350
	$4500 K/yr

*All of these activities are generic and need to be pursued for any future collider detectors, be they at an SSC or any other facility addressing the TeV physics domain. It is assumed that this work will be carried out under the rubric of advanced technology R&D, and thus no specific SSC budget line for detectors seems appropriate at this time.

also stimulate joint international R&D efforts in the future. The Task Force, at least at the beginning, is expected to a major role in initiating and organizing various workshops and study groups.

If the CDG is to discharge its coordinating role in the detector R&D, it will need to hire additional personnel. Three FTE's will be necessary to coordinate the program described in Sect. 7.1 and Table 7-1. The two major goals for the detector program during the coming year would be preparing the relevant part of the Conceptual Design Report, due in the spring of 1986, and organizing the detector program for Snowmass '86. The final Conceptual Design Report would require additional input regarding how detector needs influence the machine and the interaction regions. The Snowmass '86 study should summarize the results of all the workshops and study groups up to that time and outline specific hardware and software R&D to be pursued in the following years.

CHAPTER 8. CONVENTIONAL SYSTEMS

8.1 Accomplishments Since RDS

Following the publication of the RDS in May 1984, an effort was initiated with Parsons, Brinckerhoff personnel to consider the tasks to be addressed prior to the start of construction. This helped to define significant Phase I activities in the areas of SSC conventional facilities. The results of this effort were incorporated in the draft program plan, prepared in late June 1984.

Following the 1984 Snowmass Summer Study, preparatory work was undertaken at Fermilab, studying historical material concerning the site-selection process followed in choosing the Illinois site in 1966. This study covered an examination of the technical information about the design of the "200 BeV" machine, including the criteria that were recommended to the Atomic Energy Commission (AEC). As a by-product, it was possible to reconstruct the essential elements of the selection process, including the steps that involved the National Academy of Sciences and the AEC.

The next step was to prepare a plan and tentative schedule for the work over the next several years associated with the site and conventional facilities activities of the SSC. Elements in the plan covered the following topics:

- A Site Parameters Document
- SSC Conceptual Design
- Generic Environmental and Safety Studies

To accomplish these tasks a plan was prepared with a series of steps to be taken in the months ahead. With respect to the Site Parameters Document, a technical description of the SSC facility was prepared. This built upon the technical and conventional facilities that were described in the RDS.

A major effort involved acquiring professional engineering help for the siting studies, especially in the preparation of the Site Parameters Document, which describes in general terms the planned facility and its requirements. To acquire the needed help, DOE Chicago recommended using a firm already under contract, namely the CER Corp. Discussions were held with R. Ryan of CER, which in turn lead to a subcontract being placed with Parsons Brinckerhoff.

The development of site criteria was initiated after a thorough reading and examination of the work done prior to the founding of NAL, now known as Fermilab. The process that was followed consisted of an extended consideration of the information that would be needed to evaluate a proposed site.

Following discussions within the CDG and with the A/E personnel, the following topics emerged: Setting, Environment, Geology and Tunneling, Community Resources, Utilities, Man-made Disturbances, Climate, and Cost and Schedule.

The criteria, topics were selected with care and arranged according to the priorities suggested by the CDG. Some topics are quantitative, including magnitudes, while others are of a "softer" nature, leading to qualitative statements. A summary of the recommended criteria is shown in Table 8-1.

Longer term plans have been laid for a two-year program of A/E work leading up to the preparation of a Conceptual Design Report. The Chicago Office of the DOE set up an A/E selection process with input from the CDG. An announcement soliciting A/E services appeared in the December 6, 1984, issue of the Commerce Business Daily.

Table 8-1. Summary of Site Criteria Statements.
(As recommended to DOE)

SETTING	space for ring circumference of 60-100 miles looking for a site for a planar machine which is flat (level) or with a tilt < 1° need up to 11,000 acres
ENVIRONMENT	SSC will comply with NEPA need baseline data
GEOLOGY AND TUNNELING	long, uniform material, extensive characterization avoidance of active faults, good soil stability avoid unconsolidated solids with ground water awareness of seismic activity
COMMUNITY	staff needs: housing, education, cultural reasonable commuting times major airport, all-weather roads adequate industrial/construction resources
UTILITIES	up to 2000 gal/min of water up to 250 MW, separate feeds, outages < 2/yr
MAN-MADE DISTURBANCES	excessive noise--avoidance vibration--3 Hz is bad
CLIMATE	desirable average temperature 35° - 80°F desirable average relative humidity 25%-70%
COST AND SCHEDULE	land costs, utility rates what's being offered

The full criteria statements are contained in the Siting Parameters Document (SSC-15). The material in the Document is organized as follows:

I. SSC Project Description

II. Features of the SSC

III. SSC Siting Criteria

IV. Information Needed about Proposed Sites

Starting from a general description of the high-energy facility, the case is made for the criteria, leading up to a list of information that DOE is encouraged to seek from prospective site proposers. The document was submitted to DOE on April 15, and is available upon request.

Meetings were held at Chicago Operations for selecting an A/E firm for the conceptual design of the SSC. Four firms were interviewed: DUSAB (Daniel, Urban, Seelye, and Bechtel); Morrison-Knudsen; Parsons, Brinckerhoff, Quade & Douglas; and RTK (Raymond Kaiser, Tudor, Keller Gannon-Knight). Thorough presentations were made by each firm or joint venture. In preparation for initiating work with the selected firm, an evaluation of the scope of work was done and a description of the tasks and their priorities examined.

In June the DOE selected the RTK firm to carry out the A/E work for the Conceptual Design Report. Work has commenced in collaboration with RTK (based in Oakland, California), focusing initially on tunneling costs.

8.2 Plans

Attention within the Conventional Systems Division of the CDG is being directed to the considerable work that lies ahead. With the assistance of engineering firms, it is intended that the design work done for the RDS be extended and augmented. For the purpose of a proposal, selected design work will be attempted with the attention concentrated upon developing an overall project schedule integrated with the needs of the technical systems. Following that, a master plan will be developed to guide the subsequent work. In this phase there will be an examination of the space and facility requirements of the accelerator and research groups, including university users. The next step will be a conceptual design where attention will be paid to a number of technical problems. The tunnel requirements will be studied in much more detail, including an examination of a number of safety considerations. The integration of technical and conventional systems will be addressed and optimization carried out. Since the site will not have been chosen, generic studies will be undertaken in the area of environmental analysis, site infrastructure, utility systems distribution, etc. As before, attention will be paid to achieving an integrated schedule that will lead to efficient construction in a cost-effective manner. This will be demonstrated by a detailed cost estimate, including the needs for annual funding.

The specific work of the Conventional Systems Division is being organized under the following headings:

- Planning and Coordination
  - Administration
  - Technical Studies
  - Environmental and Safety
- Siting
  - Parameterization
  - Technical aid to DOE if needed
- Conceptual Designs
  - Proposal (Non-site-specific)
  - Master Plan
  - Conceptual Design
  - Pre-Title I
- Preliminary Design
  - Adaption of Conceptual Design
  - Advance Design
  - Mobilization

Plans for further work associated with detailed design, construction, inspection, etc. are being formulated as part of the over-all project plan.

In support of the pending magnet decisions the Conventional Systems Division is exploring the implication of the design and cost differences between colliders built using 6T or 3T magnets. The major impact is with the longer (100 mile) tunnel, required by the weaker magnetic field compared to a 60 mile tunnel needed to enclose 6T magnets. Other items such as service areas, exits, utilities, roads, etc., are different. Increased transit time for personnel at the longer ring leads to an estimate of approximately 10Δ more maintenance/service people needed in that case. Following a decision on the magnet, the site parameters document will be amended to take into account the specific physical implications of the decision.

Clarification of the magnet field and site requirements will make it possible to prepare a conceptual design (non-site-specific) for the SSC. In this phase the ideas and concepts for an SSC will be extended beyond what was accomplished during the RDS. Technical subjects concerning tunnel construction, other underground systems, safety, radiation design, possible test beams, and clustered experimental areas will be examined. Since a specific site will not likely have been chosen by DOE before March 1986, generic studies will be done with respect to environmental considerations.

When a site is selected, physical and geotechnical information will be assembled so that the earlier design work can be adapted to the specific characteristics of the site. This work will result in a final Conceptual Design where design options can be evaluated in order to achieve an optimized configuration. This will lead into a pre-Title I design and report, due in August 1987. The accomplishment of this goal will make possible the advanced design of facilities that will be needed for early occupancy on the site and rapid mobilization when the Notice to Proceed (NTP) is received from the DOE.

Current planning is aimed toward providing early access to one sector (1/12) of the collider ring for the installation of magnets, cryogenic distribution system, and a helium refrigerator within two years after NTP. This would permit the testing of prototype components under realistic conditions. Meanwhile detailed design would proceed in order to have an orderly progress into full-scale construction.

CHAPTER 9. PROJECT PLANNING & MANAGEMENT

9.1 Activities in FY 1985

Initial activities in FY 1985 involved establishing the operations and support structure for the CDG at LBL. This work included the development of administrative procedures, staffing, and coordination with LBL support groups.

Financial tasks have included the development of a chart of accounts for the CDG within the LBL account structure. While the majority of SSC costs are accounted through the LBL system, the CDG operates independently of LBL under DOE/URA contract DE-AC02-76CH03000, Account 3001. Therefore independent financial records are maintained by the CDG. The chart of LBL accounts for the CDG operation are given in Table 9-1.

A system of accounts was set up for each of the laboratory programs. The account structure for the CDG and the Laboratory efforts also reflects the reporting categories for the SSC R&D activities. This system was reviewed in detail by the Fiscal and Management Review Panel (see Appendix A). The accounts were established to reflect the costs for the major areas of research within the SSC program at each laboratory as planned by the CDG-Laboratory Agreements.

Other specific tasks have included formal agreements between the CDG and individual laboratories for work to be performed (see Section 2.2), the SSC Program Plan, the SSC Management Plan, and Field Task Proposal/Agreement. Continuing activities include budget accounting, reporting, cost estimating, and long-term planning for both Phase I and Phase II.

One of the most important tasks in the Project Planning Group is the assembly and coordination of all costs related to the various magnet design styles. During the spring of 1985, a complete review of the magnet system cost estimates for all of the candidate superconducting magnet types being considered for the SSC main ring will be carried out. In addition, cost estimates are being re-examined for other major accelerator systems and for conventional construction areas to provide appropriate cost data for a projected complete SSC facility utilizing each of the candidate magnet styles.

Table 9-1. Chart of LBL Accounts for the CDG.

8390		SSC Central Design Group
		CDG Directorate (subs 1-4)
	01	General
		Program Management (subs 5-21)
	05	Program Planning and Technical Coordination
	20	Administrative Support
		Accelerator R&D (subs 22-59)
	22	General
	25	Theory & Computation
	30	Accelerator Systems
	40	Magnets
	50	Injector
		Conventional Systems (subs 60-69)
	60	Planning & Coordination
	61	Site Criteria
	62	Conceptual Design
	63	Tunnel Concepts
8391		Central Design Group Equipment Purchases
	01	Administration
	05	Program Planning & Coordination
	25	Accelerator R&D
	60	Conventional Systems
		Capital Improvement Project
	80	Improvements, 90, 4th Floor
	81	Conference Room
	82	Ventilation Modifications, 90, 4th Floor

For the overall cost comparisons for the total SSC project, the same major Work Breakdown Structure (WBS) and cost categories described in the RDS are being used:

1.1 Project Management
1.2 Central Laboratory Facilities
1.3 Injector Facilities
1.4 Collider Facilities
1.5 Experimental Facilities
1.6 Systems Engineering and Design
1.7 Contingency.

All current costs are developed in FY 1985 dollars. In cases where the RDS costs have been utilized, they were scaled to allow for a nominal FY 1984-85 escalation rate (5% was used for the estimate comparisons). Where the costs were developed or reviewed explicitly for the current study, actual FY 1985 costs are used directly.

The various magnet system detailed costs are being estimated both by participating laboratory magnet groups and by industrial manufacturing firms; they will be assembled, reviewed, and analyzed by the CDG for uniformity, consistency, and completeness. In addition to the specific magnet style designs, as part of the overall cost development, study, and analysis, certain "variable" issues are being considered separately from the basic magnet styles. The effects of variation in the magnet aperture are considered for high-field cosine-theta magnets and low field superferric magnets, and scaling factors are being developed for certain of the key magnet components. Some analysis will be done to re-examine the overall cost implications of magnet length variations, lattice cell structure, number of lattice quadrupoles, etc.

A Cost-Estimating Task Force has been established to assemble, review, and analyze the total information in a manner which will facilitate comparisons of the various magnet styles.

The detailed cost information for each magnet style is being developed by the laboratory magnet groups. A WBS format has been developed by the CDG to provide data in the same categories for each magnet style to the maximum extent possible. The format is similar to that used for the 1984 estimates in the RDS.

In addition to the laboratory efforts, two industrial firms with experience in the superconducting magnet area, General Dynamics-Convair Division and Westinghouse Electric Corporation, are each providing independent manufacturing plans and cost estimates for two particular magnet styles C and D. These two styles provide examples of both high-field and low-field magnet design. The two contracts started in April, 1985, and are due to be completed by July 1, 1985. Five specific tasks are being studied and developed under these industrial contracts:

1) Develop a comprehensive manufacturing sequence and flow chart depicting all major manufacturing operations from receipt of raw materials and vendor-supplied components through final magnet assembly. Significant inspection and test operations should also be indicated.

2) Prepare a plant layout for most efficient work flow for large quantity production of these magnets. Estimate size and cost of production facilities.

3) Prepare schematic designs for the required tooling for producing these magnets. Estimate tooling production rate and determine tool quantity requirements. Estimate tool design and fabrication costs.

4) Consider and list all in-process and acceptance-test requirements and associated equipment. Estimate test-span times and determine the quantity of test stations required to support the necessary production rate. Estimate the test equipment and operation costs.

5) Prepare a detailed cost estimate for the magnets. This should be supported by vendor quotations for as many of the raw materials and subassembly components as practicable. Internal estimates should be generated to supplement the vendor quotations as necessary.

There are five magnet style categories considered in the cost studies that are described below:

Type A is a high-field (6T) superconducting magnet utilizing a two-layer, collared cosine-theta coil (stainless steel collars), cold iron for the flux return, and arranged with two bores side by side in one single yoke (i.e., 2-1), all contained in a single cryostat. The coil i.d. is 4 cm and the bore tube i.d. is 3.28 cm. The magnet has an effective magnetic length of 16.6 m and an overall length of 17.6 m. For a 20 TeV SSC, 4200 such magnets would be required if the central field is 6T. The Type A design has been developed in collaboration between LBL and BNL.

Type B is a high-field (5T) magnet utilizing a two-layer, collared cosine-theta coil (with aluminum collars) and no cold iron. The outer vacuum vessel is a warm iron shell that provides magnetic shielding; the magnets are all single bores (1-1). The coil i.d. is 5 cm; the overall length is approximately 12 m (magnetic length 11.25 m). Approximately 14880 such magnets are required for 5T operation. Style B was developed by FNAL.

Type C is a low-field (3T) superferric magnet. This magnet has cold iron and is arranged with two magnetically decoupled units to be mounted one above the other in a single cryostat. The iron gap is 2.54 cm high and approximately 3.2 cm wide for the useful aperture. Each bore of the magnet has three separately energized coils used for tuning out unwanted multipoles, and each coil set must follow a prescribed ramping program sequence.

These magnets are fabricated in 35 m elements. Current design has three 35 m elements preassembled in a single cryostat with a quadrupole and correction coils at the laboratory site to form 115 m units. Approximately 1000 each of these long units (or 4000 of the fabricated 35 m units) are required for the SSC. Style C was developed by TAC.

Type C* is a (1-1) version of type C with the same magnetic geometry and parameters, but utilizing two independent magnets in separate cryostats. Hence for C*, 2000 each of the long units (or 8000 fabricated 35 m units) would be required for the SSC. Style C* is also being developed by TAC.

Type D represents a magnetically and cryogenically decoupled (1-1) version of style A. Magnet parameters are similar. Approximately 8400 units at 6T central field operation are required for the SSC. Style D is being developed by a BNL, FNAL, and LBL collaboration.

The Cost Estimating Task Force (CETF) will assemble the above data on dipole magnet costs. The data will be analyzed together with the final magnet report from the Aperture Task Force in order to normalize costs to the prescribed aperture. The CETF final report will also include cost information from the Magnet Systems Group on cryogenic systems, installation, and other accelerator systems. The report will also address cost variations for conventional systems appropriate to each magnet design style.

The final CETF report together with reports from the Accelerator Physics Division regarding magnet field quality, the Low Temperature Operations Task Force, the Operations and Commissioning Task Force, and the Power Supply-Quench Protection Task Force will form the body of information available to the Magnet Selection Advisory Committee.

The magnet selection process described above is a major part of the CDG effort for the last half of FY 1985 and involves nearly all of the CDG Divisions. Other specific R&D efforts are described elsewhere in this report. The total CDG effort for FY 1985 involves Management, Planning, Accelerator Physics, Accelerator Systems, Injection Systems, Superconducting Magnet Program, and Conventional Systems (including A/E contracts). The planned vs. actual costs for the CDG program through April, 1985, are shown in Fig. 2-3, p. 27.

9.2 Schedules

The overall goals and major milestones for the SSC R&D program are summarized in Fig. 2.4, p. 30. In FY 1986 the program will encompass more details of the overall SSC technical systems in a sufficient manner to provide a construction proposal with associated cost information; however, the superconducting magnet program will remain as the major focus of the R&D activities. The most significant milestone for FY 1986 will be the submission of a SSC Non-Site-Specific Conceptual Design Report in April 1986.

In order to make a significant demonstration of major component feasibility together with cost estimate verification, the FY 1987 R&D efforts must increase substantially over those of FY 1985 and FY 1986 (see Table 9-4). The CDG activities will require a significant increase in manpower to plan properly all aspects of the technical systems of the SSC. Approximately one-third of the CDG budget ($5M) will be used for engineering services to provide for pre-Title I Design & Planning for the Site and Conventional Facilities. Detailed planning and coordination of all efforts will be vital to an expeditious and efficient construction start. In the area of SSC technical systems, the magnet program will remain as the largest effort; however, other accelerator systems for the SSC including the injection accelerators will become a more substantial part of the total program.

In general, the CDG, building on the accelerator physics and engineering studies of FY 1984 and FY 1985, will carry out design-optimization studies based on a single magnet style. This program will encompass all accelerator systems including the injection accelerator systems. As specific system-design concepts evolve, studies will be undertaken to understand and optimize the overall operational reliability and performance of the SSC.

The activities of the Accelerator Physics (AP) Division are intimately meshed with all of the accelerator activities. In general an iterative process is involved between theoretical projections and component designs. As seen in Figs. 9-1(a) and 9-1(b) the AP Group will provide initial parameters for major systems in FY 1985 which serve as the design guide. The design R&D may alter or require new calculational evaluations. The Conceptual Design Report of April 1986 will represent a complete SSC design for overall systems. R&D on subsystems and components will continue through FY 1987.

The AP Group activities on lattice design, aperture specifications, and field quality are vital to the magnet-development program. Studies of

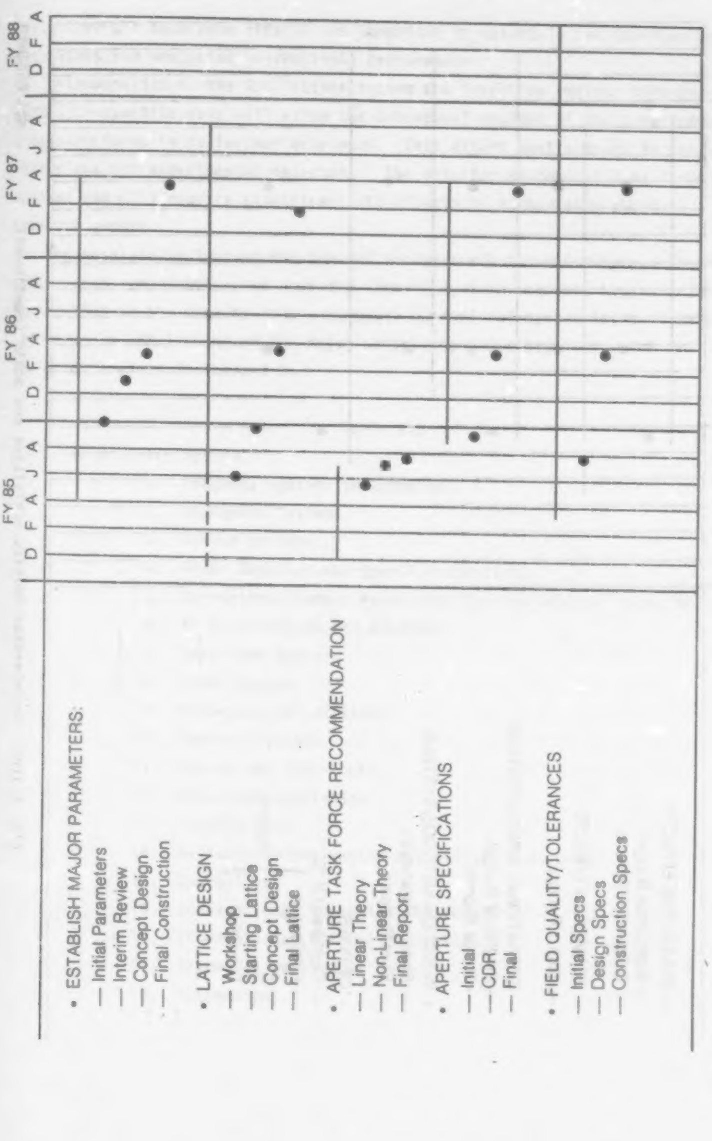

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Fig. 9-1(a). Accelerator Physics activities and goals.

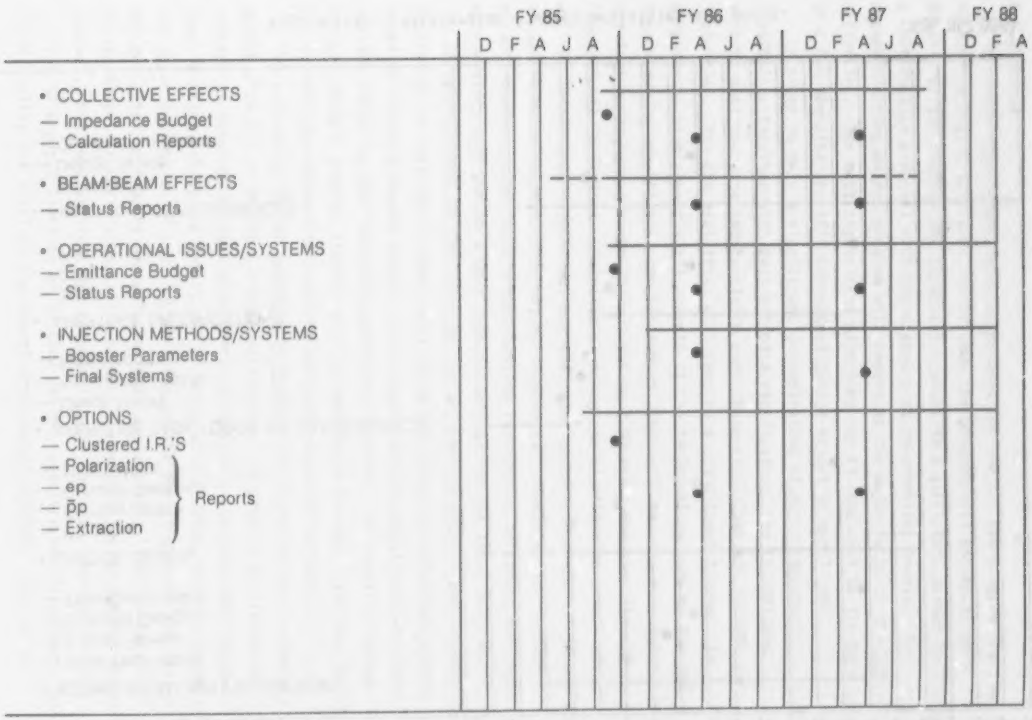

Fig. 9-1(b). Accelerator Physics activities and goals (continued). XBL 857-9861 collective and beam-beam effects are important to materials and fabrication techniques and projected operational performance.

Determination of the SSC lattice system and insertion regions together with site-specific data will allow the conceptual designs of the experimental area structures to be further developed. This effort must proceed in concert with plans for experimental detectors. The detector systems will be large and complex and will require significant R&D efforts by high-energy physics research groups.

The Accelerator Systems for the SSC includes all the main storage ring systems and components apart from the superconducting magnets; however, the integration of the magnets into a complete operational system falls in this category. A WBS listing of the major components and subsystems which are included is given in Table 9-2.

Table 9-2

1.3.3 Accelerator Systems

    1. (Magnet) Systems Integration
    2. Cryogenic Systems
    3. Vacuum Systems
    4. Power Supplies and Quench Protection
    5. Correction Element Power Supplies and Quench Protection
    6. RF Acceleration and Feedback
    7. Injection System
    8. Abort System
    9. Beam-Loss Calculations
    10. Control Systems
    11. Safety and Interlocks
    12. Beam Instrumentation
    13. Installation
    14. Reliability Evaluation and Quality Assurance
    15. Operations
    16. (Conventional Mechanical Systems)
    17. (Conventional Electrical Systems)
    18. Insertion Regions
    19. Extraction

Planning details for the Accelerator Systems activities are provided in Figs. 9-2(a) and 9-2(b). The magnet systems integration is an important part of this program. While the prototype magnets will be individually tested as they are made, assessment of their behavior as part of a complete system is crucial in evaluating their effectiveness and reliability for the SSC. The first test of a set of magnets (Half-Cell Test) is projected for FY 1987. Overall systems tests for engineering design and reliability studies will continue into FY 1988 and beyond.

Cryogenics, vacuum, and power-supply systems are closely tied to the magnet design and represent significant efforts for FY 1986 and FY 1987. The other systems noted in Figs. 9-2(a,b) will be examined in sufficient detail for the Conceptual Design Report. Fabrication of prototype units and testing are indicated in the schedule.

With regard to the Magnets, an extensive examination of a range of basic dipole magnet types is currently being carried out, with a selection to be made in the last quarter of FY 1985. Building on the extensive preselection design work under way, the final prototype design will be completed in early FY 1986, and prototype fabrication will begin at a modest, budget-limited rate. Efforts will be focused on optimizing this design with regard to costs and performance. The program will also include engineering studies of quadrupoles and other special units such as correction-element spools, injection-system magnets, and insertion-region magnet elements.

Most important will be continuation of the development, in collaboration with U.S. industry, to improve the current-carrying capacity and other characteristics of commercially available superconducting material. Prior to the beginning of the recent improvement program, wire containing filaments capable of transporting 1800 A/mm^2 was commercially available. The Reference Design Study assumed in its cost estimates that an improvement to 2400 A/mm^2 could be effected by R&D prior to SSC construction. This goal has already been exceeded, and even higher values may be available for the SSC during the coming year.

In FY 1987, after individual tests of the first group of prototype dipoles for field quality and performance and installation and operation of the Half-Cell Test, it is planned that approximately 40 additional dipole units be

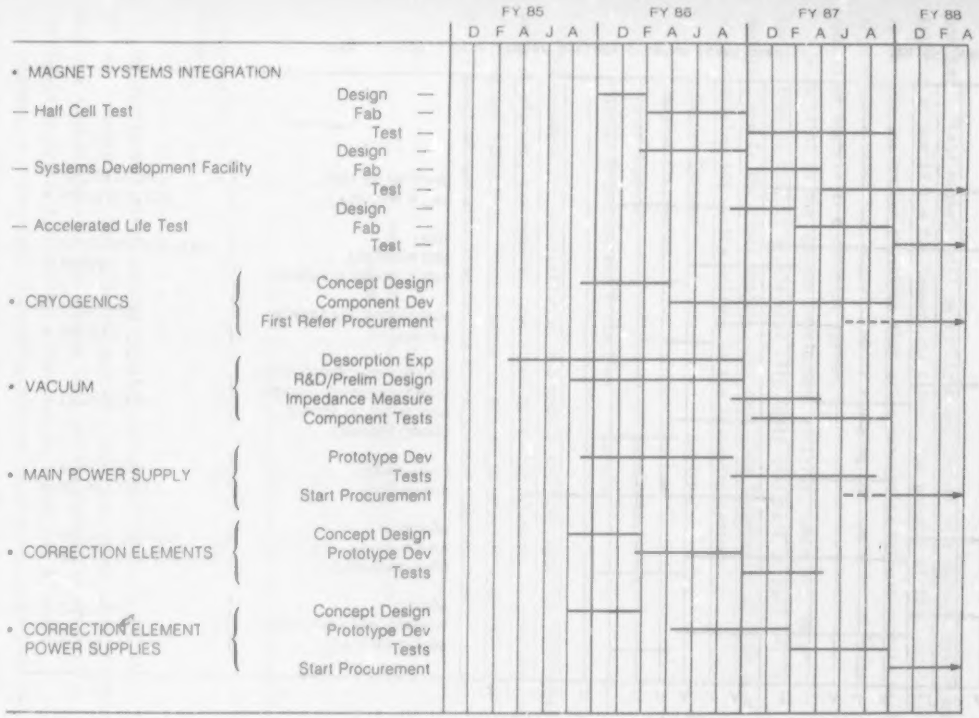

Fig. 9-2(a). Accelerator Systems program.

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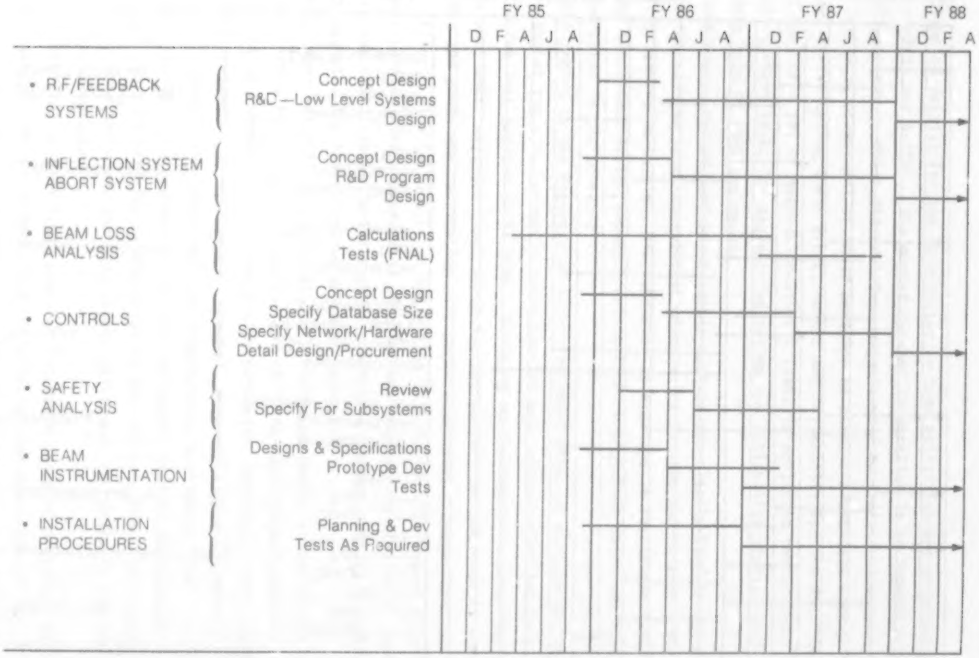

Fig. 9-2(b). Accelerator Systems program (continued).

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produced. These magnets will be utilized and tested in a Systems Development Facility at one of the DOE laboratory sites. The purpose of this facility is to generate and answer questions that arise concerning the engineering design of components other than magnets, while studying the operation of large numbers of magnets as a coherent system.

In addition to the Systems Development Facility, there will be an installation to conduct Accelerated Life Tests on a half or full cell of magnets close to the final design. The resulting information will be used to further develop and verify designs in the following systems:

- Magnet Systems
- Magnet Cryogenics
- Power Supplies
- Quench Detection and Protection
- Controls
- Vacuum
- Correction Coils
- Safety

The schedule for fabrication of R&D models and preproduction prototype units of dipoles, quadrupoles, and other main ring elements is provided in Fig. 9-3 and Table 9-3. This program is geared to provide a 35-cell test (~1/12 ring) of the main ring in the third year of construction.

Table 9-3
S.C. Magnet Program -- Magnet Production Plan
During Construction of the SSC

	FISCAL YEAR					
	88	89	90	91	92	93
Number of Cells Produced	5	30	85	150	150	

The development of an optimum Injector system will begin in FY 1986. The desired parameters of the injected beam will have been established in concert with the determination of the storage ring lattice magnet characteristics. The injection system is currently visualized as a sequence of three accelerators, a 1-GeV linac, low-energy booster synchrotron (approximately 70 GeV), and a high-energy booster with energy in the 1-TeV range. Studies will determine the optimum energy and beam characteristics of each of these injector accelerator systems. Work will begin on the overall lattice system for both booster accelerators and the required magnet parameters. In particular for the high-energy booster, a program will be initiated to provide prototype models of the superconducting magnet designs. While the parameters of the injected beam will be matched to the requirements of the main storage ring, it is important that the overall injection system of cascaded accelerators be designed for maximum reliability in operations. This will require careful consideration of the design and component specifications for the man subsystems for each of the injector accelerators

Figure 9-4 shows the general plan for the injectors. An optimized overall design will be provided for the Conceptual Design Report. Details of the systems will be developed in late FY 1986 and FY 1987. The development of high priority components will commence in FY 1987.

For the Conventional Systems, a cost estimate based on a "median" site was featured in the RDS. For FY 1986 an important supplement to that will be the development of cost ranges to be expected for potential real site variations. In addition, the non-site-specific features of the conventional systems will need to be developed further to optimize their adaption to scientific need. Further studies of utilities distribution and organization of other site services and arrangements will also be needed to assure cost effectiveness of the conceptual design.

Selection of a favorable site for the SSC will be crucial for maximizing its cost effectiveness. Accordingly, it will be important to study extensively the potential impact of the SSC on its environment and the implications of various types of environment for SSC costs. It is expected that this process will continue throughout the period prior to site selection.

As seen from Fig. 2-4, p. 30, the site selection is projected as a major milestone in the first quarter of FY 1987. The achievement of this milestone would give access to the site-specific information that is required to provide the conceptual design. For example, the final site geology and topography would allow a determination of tunneling techniques to be used. Power and cooling-water systems could be more accurately specified and preparation made for initial site services. A master plan for the layout of the central

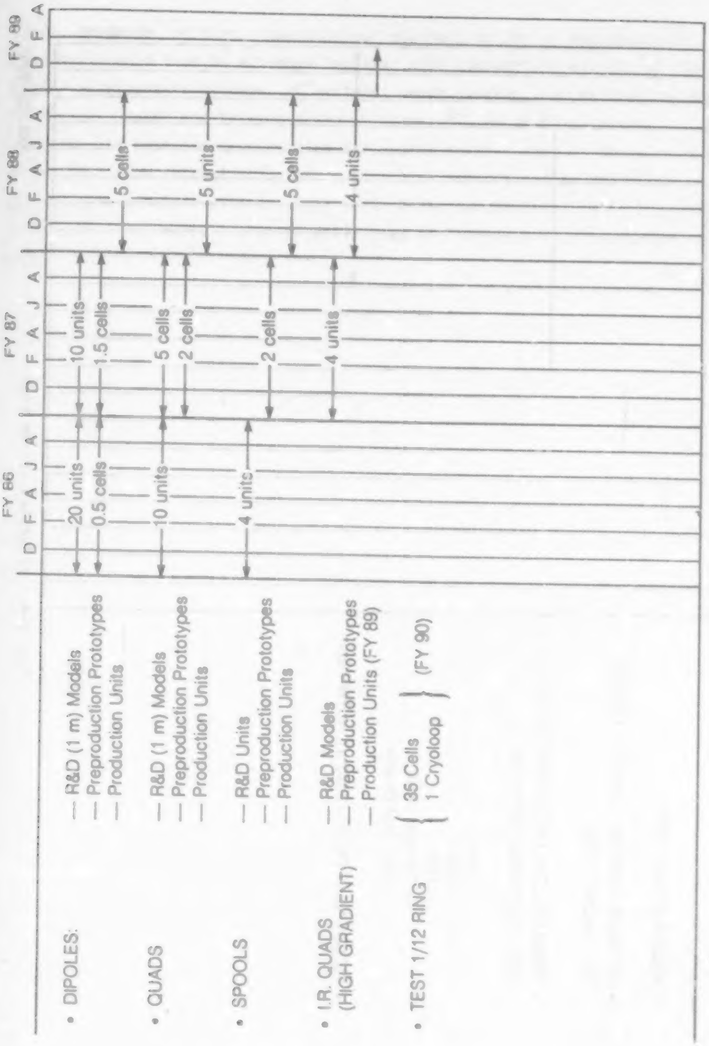

Fig. 9-3. Superconducting magnet fabrication plan.

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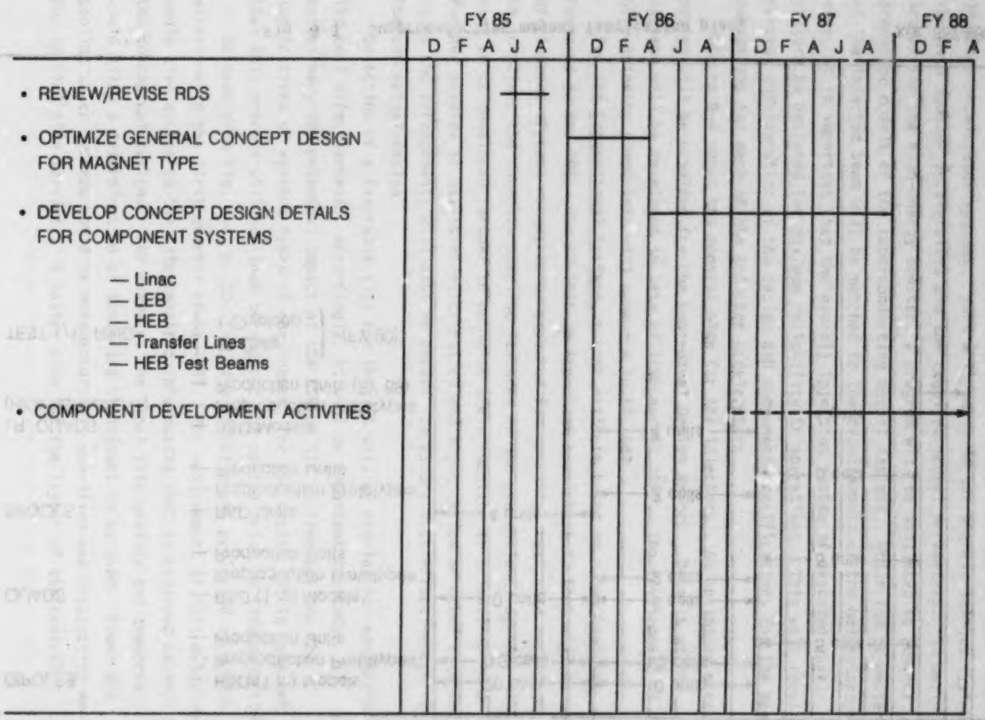

Fig. 9-4. Injection system plan. XBL 857-9867

office, research offices, laboratories, assembly building, and warehouse facilities could then be extended together with appropriate structures for housing refrigerator systems, rf systems, power systems, and various support facilities. Roads and transportation systems will be of significant importance to both the construction and operation of a ring on the size scale of the SSC. The determination of construction methods and an optimized construction schedule will be vital part of the conventional facility effort in FY 1987. The overall plan of activities is indicated in Figs. 9-5(a) and 9-5(b).

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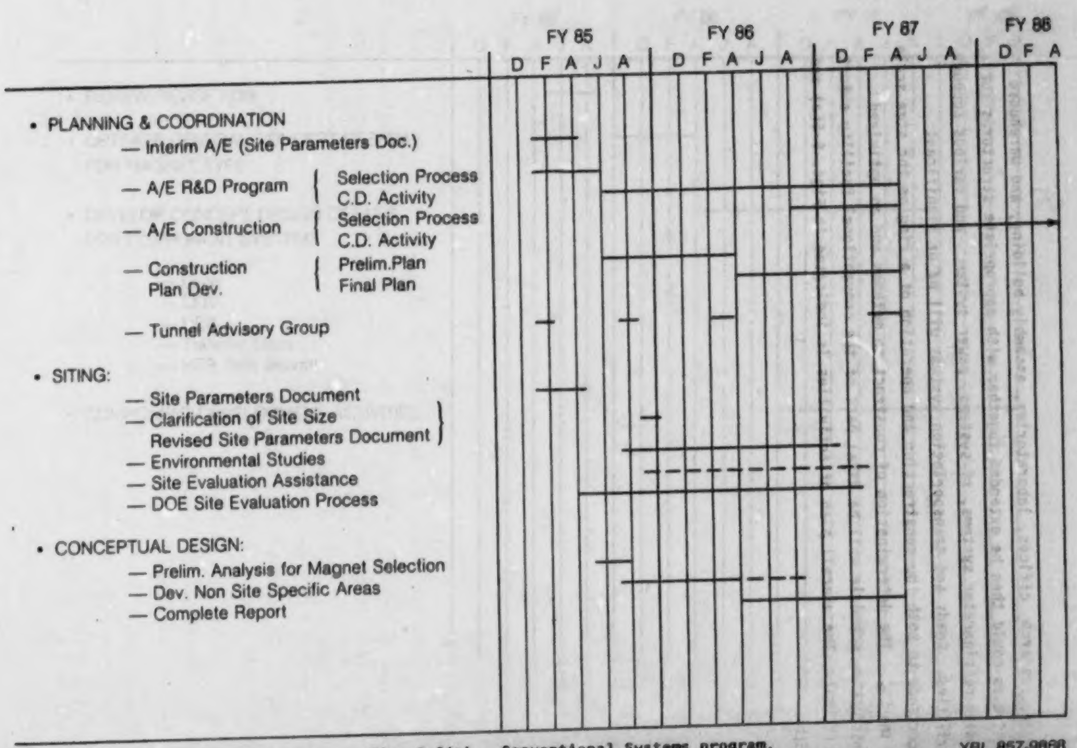

Fig. 9-5(a). Conventional Systems program.

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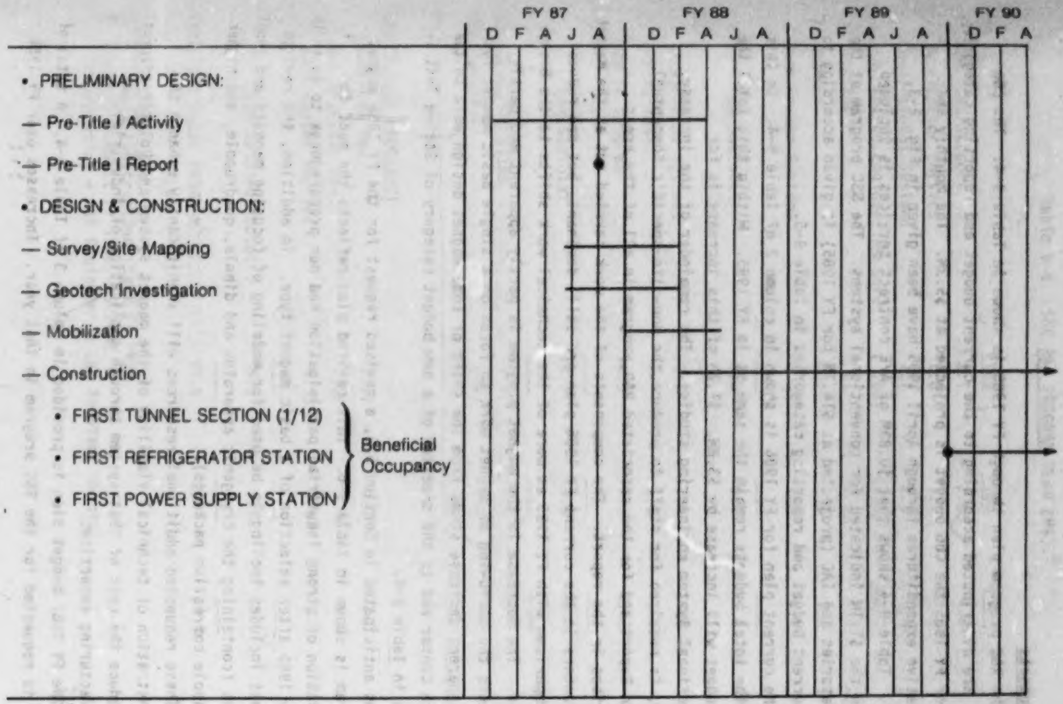

Fig. 9-5(b). Conventional Systems program (continued).

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9.3 Budgets

The R&D program plan through FY 1988 is shown in Table 9-4. The CDG costs are distributed according to the current budget and reporting categories.

For FY 1985 the CDG budget is projected at $5.3M. The monthly and cumulative expenditures through April 1985 have been given in Fig. 2-3, p. 27. Table 9-4 shows that $0.83M of A/E contract services is included within the $1.1M indicated for conventional systems. The SSC program at the laboratories and TAC (projected at $14.7M for FY 1985) is given according to the current budget and reporting categories in Table 9-5.

The current plan for FY 1986 is shown in column 2 of Table 9-4. In this plan the total budgets remain the same as in FY 1985. Within this total the CDG budget will increase by $3.8M. $1.2M of this increase is for Conventional System engineering studies. The remainder of the increase, $2.6M, is required for staff to produce the non-site-specific Conceptual Design Report and for the associated R&D program in all of the areas described in the report. The components of the work carried out at the Magnet R&D Centers in the current FY 1986 plan are still dominant, but are reduced by comparison with FY 1985 as more of the technical work shifts to the Design Center. The decrease in the magnet program is partly apparent and partly reflects the narrowing of magnet work to focus on a single basic magnet type. The apparent decrease stems from the shift of some magnet design work to the Design Center and to the creation of a new budget category of String Test as shown in Table 9-4.

As anticipated in Section 5.6, a revised request for the FY 1986 magnet program is shown in Table 9-6. This revised plan reflects the need for initiation of strong industrial participation and our preparedness to do so in early 1986 after selection of a basic magnet type. In addition, the revised request includes tooling to be used for modeling of focusing magnets and spool pieces (containing the cryogenic apparatus and dipole, quadrupole, and higher multipole correction packages).

These requested additional resources will significantly enhance the demonstration of technical viability of the magnet system and bolster efforts to reduce the cost of that system through application of industrial manufacturing expertise.

The FY 1987 budget plan is provided in column 3 of Table 9-4. A total of $55M is requested for the SSC program in that year. Increases over FY 1986

Table 9-4. SSC R&D PROGRAM PLAN (M$).[a]

CDG	FY85	FY86	FY87	FY88
Adm/Plan/Support	2.1	2.65	4.0	2.0
Accelerator Physics	1.0	1.4	2.0	2.0
Conventional Systems	1.1	2.5	7.0	—
Purchased Engineering Serv.	(.83)	(2.0)	(5.0)	—
Injector	0.1	0.5	1.0	5.0
Magnets	0.5	1.1	1.3	4.0
Accelerator Systems	0.5	1.0	1.7	5.0
CDG Subtotal	5.3	9.1	17.0	18.0
LAB				
Accelerator Systems	0.7	1.9	10.3	15.0
String Test	---	1.5	2.5	7.0
Magnet Program	14.0	7.5	25.2	13.0
Lab Subtotal	14.7	10.9	38.0	35.0
SSC Total Operating	20.0	20.0[b]	55.0	53.0
SSC Equipment	0.5	0.5	5.0	10.0
LAB RELATED PROGRAMS				
Supercon Dev.	1.71	1.7	2.0	
Cryo-Systems Dev.	1.66	1.66	2.0	
Accelerator Physics	1.63	1.63	2.0	
Lab Related Subtotal	5.0	5.0	6.0	6.0
EFFECTIVE TOTAL PROGRAM[c]	25.5	25.5	66.0	69.0

---

[a] Assuming construction start FY 1988

[b] Revised request FY 1986 - $27.0M

[c] SSC Operating + SSC Equipment + Lab Related Subtotal

Table 9.5. FY 1985 Budget Plan for Magnet R&D Centers.

Monthly Reporting Categories	BNL	FNAL	LBL	TAC	
General	800	340	115	825	SSC ($14.675M) Program
Magnet Models	2200	3225	395	2810	
Analysis	--	-	125	130	
Inst. & Measmt.	--	--	155	--	
Tooling	800	--	--	630	
Mag. Measure Devel.	400	--	--	--	
P.S./Q.P.	280	--	--	--	
Cryotesting	500	--	--	--	
Facility Devel.	--	340	--	605	
	4980	3905	790	5000	
S.C. Dev.	900	400	410	--	Lab Related ($5M) Programs
Cryo Dev.	770	890	--	--	
	1670	1290	410	--	
Accel. Physics	--	830	800	--	

Table 9-6. Revised Request. FY 1986 SSC Magnet Program Plan.[a]

	M$
Gen/Adm/Support	1.0
Tooling	2.0
20 Dipole Models (1 M)	1.5
5 Dipole Prototypes	2.0
Operations/Testing	1.5
10 Quadrupole Models	1.0
4 Spool Models	0.5
Industrial Participation (5 magnet models including tooling by industry)	5.0
Total	14.5[b]

[a] Plan supports production of one half cell of magnets.

[b] Present Budget Plan indicates $7.5M. (See Table 9-4)

are requested in all areas of the CDG program, both for engineering studies of Conventional Systems and further R&D in technical systems. A three-fold increase is required of the SSC laboratory programs to accomplish all of the tasks under Accelerator Systems (as indicated in Section II-3 above) and to strengthen the superconducting magnet program. A breakdown for the requested magnet program is provided in Table 9-7. This plan, in particular for main ring dipoles, is essential in providing a significant number of magnets for systems testing and in validating cost estimates, thereby laying the groundwork for a timely construction start. At this level of support the magnet production plan outlined in Table 9-3, p. 111, will be feasible.

Table 9-7. FY 1987 SSC Magnet Program Plan.[a]

	M$
Gen/Adm/Support	2.0
Tooling	2.5
10 Dipole Models (1 M)	0.8
20 Preproduction Prototype Dipoles	6.0 (Labs)
20 Preproduction Prototype Dipoles	6.0 (Industry)
Operations and Testing	4.0
5 Quadrupole Models	0.5
8 Quadrupole Prototypes	1.6
Spool Pieces (8 units)	0.8
4 High Gradient I.R. Quadrupole Models	1.0
Total	25.2[a]

---

[a] Does not include magnet models for the booster accelerators.

Table 9-8. FY 1988 SSC Magnet R&D Program[a] Plan.

	M$	
Gen/Adm/Support	2.0	
Tooling	2.0	
4 Dipole Models (1 M)	0.3	
6 Preproduction Prototype Dipoles	2.0	Labs and/or Industry
6 Preproduction Prototype Dipoles	2.0	
Operations and Testing	3.0	
5 Quadrupole Models	0.5	
5 Quadrupole Prototypes	0.5	
Spool Pieces (2 units)	0.2	
2 High Gradient I.R. Quadrupole Models	0.5	
Injection System Models & Prototypes (HEB, LEB, Transfer Lines, Kickers)	4.0	
Total	17.0	

---

[a] Total CDG and Lab efforts

The FY 1988 R&D program assumes a construction start in 1988. Accordingly, as shown in column 4 of Table 9-4, a decrease in R&D Administration and Support is projected, as well as a decrease in the Superconducting Magnet R&D effort. Expanded development efforts are required for the many components of the accelerator systems area and the injector. Continued operation of the Systems Development Facility and operation of the Accelerated Life Tests will be a significant part of the FY 1988 R&D program. Table 9-8 shows the projected elements of the FY 1988 magnet R&D program. A phase-out of the prototype development of main ring dipoles is indicated together with a significant increase in models and prototypes for the various standard accelerator systems needed for the facility.

The total SSC Accelerator R&D program related to construction is plotted in Fig. 9-6 with projections to the end of the construction period.

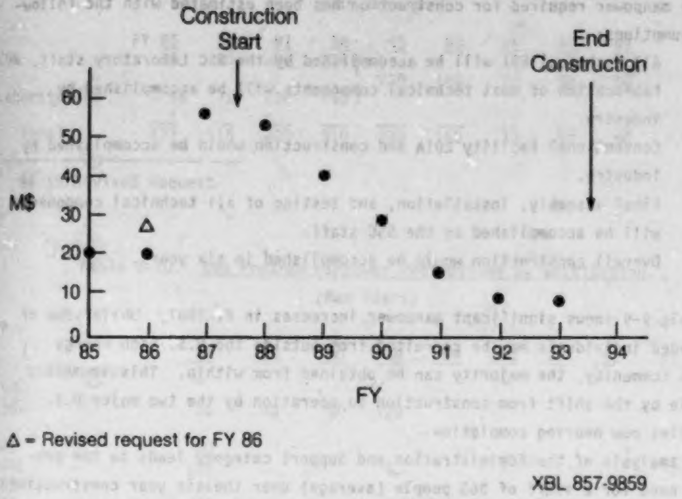

Fig. 9-6. SSC R&D Program Projection.

9.4 Manpower

Table 9-9 projects the scientific manpower levels for the SSC Research and Development program through FY 1993. Tables 9-10 and 9-11 provide a further breakdown by institution and task of the manpower numbers within the CDG and at the laboratories through FY 1988. The distinction between CDG and existing laboratories is extended through FY 1988. Although this is projected into the first year of construction only, it is anticipated that the existing laboratories will be strongly involved beyond FY 1988 while the SSC organization is being built up at the chosen construction site. However, the nature of the involvement will depend on many factors which cannot be fully evaluated at this time. Thus only an overall R&D projection is provided beyond FY 1988.

The manpower required for construction has been estimated with the following assumptions:

1. All technical EDI will be accomplished by the SSC Laboratory staff.
2. Fabrication of most technical components will be accomplished by industry.
3. Conventional facility EDIA and construction would be accomplished by industry.
4. Final assembly, installation, and testing of all technical components will be accomplished by the SSC staff.
5. Overall construction would be accomplished in six years.

Table 9-9 shows significant manpower increases in FY 1987. While some of the needed individuals may be recruited from outside the U.S. high energy physics community, the majority can be obtained from within. This is made possible by the shift from construction to operation by the two major U.S. facilities now nearing completion.

An analysis of the Administration and Support category leads to the projected need for a staff of 363 people (average) over the six year construction period. Similar breakdowns have been used for the categories of EDI and Assembly and Testing.

The overall results for each category are shown in the Fig. 9-7,8,9.

Table 9-12 summarizes the average manpower in each category over its period of operation within the six-year construction time. In line with the assumptions, the manpower was estimated according to the following categories: Administration and Support (AS), Engineering, Design and Inspection (EDI), and Assembly and Installation (AI). The categories of EDI and AI were analyzed for the major technical systems as follows: injection systems, collider ring magnets and cryogenics, and other systems, (rf, power supplies, controls, beam dump, etc.)

Table 9-9. Overall SSC R&D Program Manpower Projections.
(Man Years)

	FY 85	86	87	88	89	90	91	92	93
CDG	25	43	80	120	230	160	70	50	50
Laboratories	96	72[a]	220	190					
Total	121	115	300	310	230	160	70	50	50

---

[a] 96 in Revised Request

Table 9-10. R&D Program Manpower Projections by Institution.
(Man Years)

	85	86	87	88	89	90	91	92	93
A. SSC Program									
CDG	25	43	80	120					
BNL	40								
FNAL	25								
LBL	6								
TAC	25								
Lab Total	96	72[a]	220	190					
SSC Total	121	115	300	310	230	160	70	50	50
B. Related Laboratory Programs									
BNL	12								
FNAL	20								
LBL	8								
Lab Total	40	40	40	40					
Total Manpower	161	144	340	350					

---

[a] Lab Total = 96 based on Revised Request for FY 1986

Table 9-11. SSC R&D Program Manpower Projections by Task for Central Design Group.
(Man Years)

	FY85	FY86	FY87	FY88
Management	4.5	6	9	5
Project Plan	4.0	5	8	4
Accelerator Theory	6.0	9	12	12
Accelerator System	5.0	10	17	44
Injection	1.0	2	5	19
Magnets	1.5	6	8	36
Conventional Facilities	3.0	5	20	0
	25.0	43	80	120

Table 9-12. SSC CONSTRUCTION PROJECT - Estimated Staff Levels.

Category	Average Staff (Heads)	Activity Period (Years)
Administrative Support	360	6
EDI		
Injection Systems	135	4
Magnets/Cryogenics(Main Ring)	237	6
Other Systems (Main Ring)	71	5
Assembly/Installation		
Injection Systems	266	3
Magnets (Main Ring)	768	5
Other Systems	190	4
TOTAL	2,027	
PEAK	2,300	
SIX YEAR AVERAGE	1,650	

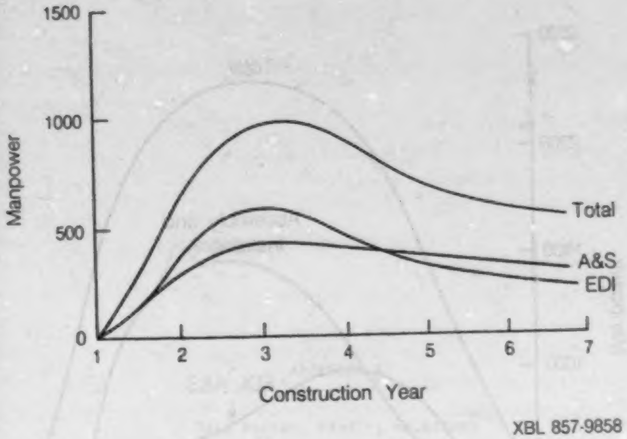

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Fig. 9-7 Manpower loading for administration and support and for EDI (total) over the six-year construction period.

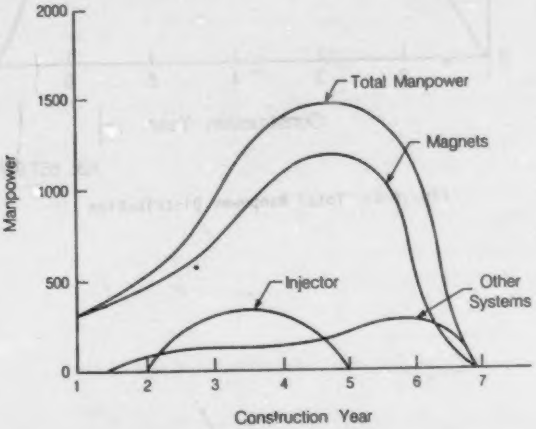

Fig. 9-8. Assembly and installation manpower distribution for magnets, injector, and other systems.

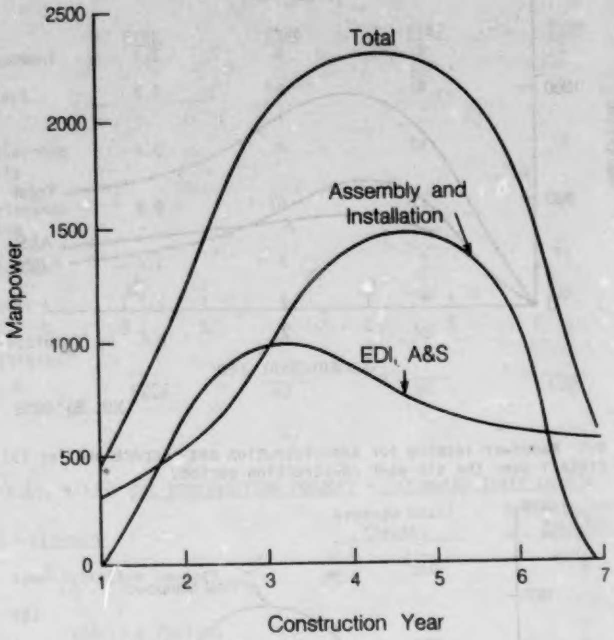

Fig. 9-9. Total Manpower Distribution

APPENDIX A

Task Forces, Panels, Workshops

SSC Interim Report - Appendix A

Workshops, Panels and Task Forces Conducted by SSC/CDG Since 10/1/84:

TITLE PAGE

Accelerator Physics:

1. Aperture Workshop and Task Forces (A-G) (Chao) 130
2. Impedance Workshops (Bisognano) 136
3. Clustered IR Study Group (Chao) 137
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5. Task Force on Low Temperature Operation of the SSC (McAshan) 143

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General CDG Administrative:

1. Business Affairs and Management Advisory Panel (Matyas) 160

Detectors:

1. Task Force on Detector R&D for the SSC (Gilchriese) 161

Name: Aperture Task Force

Charge:

To evaluate the apertures for the various magnet types suggested for the SSC.

Task Force Sub-groups:

Group A -- Test Lattices (E Courant, Chair)
Group B -- Aperture Criteria (D. Edwards, Chair)
Group C -- Magnet Errors (E. Fisk, Chair)
Group D -- Database, networking (S. Peggs, Chair)
Group E -- Tracking (A. Dragt, Chair)
Group F -- Analytic Methods (C. Leemann, Chair)
Group G -- Experiments (H. Edwards, Chair)

Task Froce Members:

Group coordinators (listed above)
A. Chao
J. Peterson

Name of Initiating Workshop: Aperture Workshop

Workshop Leader: A. Chao

Workshop Date: November 5-9, 1985

Workshop Members: (see attached listing)

Task Force Meetings:

December 3-5, 1984/Group A/BNL/12 participants
December 3-5, 1984/Group C/CDG, Berkeley/9 participants
December 17, 1984/Task Force Meetings/CDG, Berkeley/10 participants
February 7-8, 1985/Group C/CDG, Berkeley/9 participants
February 19, 1985/Task Force Meeting/FNAL/9 participants
March 4-6, 1985/Group E/CDG, Berkeley/14 participants
March 11-12, 1985/Group C/TAC/7 participants
March 14-15, 1985/Group D/CDG, Berkeley/16 participants
April 22-23, 1985/CDG, Berkeley (Review Meeting)/47 participants
April 24, 1985/CDG, Berkeley (Task Force Meeting)/9 participants
May 17-18, 1985/Group D, Linear Aperture/CDG, Berkeley/3 participants
June 6, 1985/Group D, Linear Aperture/FNAL/3 participants
July 1985/Group E/Location undetermined/15 participants (estimated)

Reports Generated by the Task Force:

SSC Aperture Workshop Summary (SSC-2)
Aperture Task Force Report (SSC-3)
Aperture Task Force Report (SSC-11)
Interim Reports (from several groups, some completed, others in progress)
Status Report #2 --August 1985

Appendix 11. SSC Aperture Workshop Participants
November 5-9, 1984

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Name: Impedance Workshops

Leader: J. Bisognano

Workshops:

December 6, 1984/ LBL/7 participants
June 26-27, 1985/CDG Berkeley/tentatively 15 participants

Charge:

To examine the impedance issues relative to the design of the SSC.

Reports Generated:

First report by J. Bisognano appeared as a paper in particle accelerator conference, May 1985, (Vancouver).

Name: Clustered IR Study Group

Leader: A. Chao

Members:

A. Chao
M. Furman
D. Groom
D. Johnson
C. Leemann
P. Limon
D. Neuffer
S. Peggs
L. Schachinger
W. Swanson
R. Talman
T. Toohig

Name of Initiating Workshop (if any): None

Meetings:

April 25, 1985/ CDG, Berkeley
June 6, 1985/CDG, Berkeley

Charge:

To study the option of clustered interaction regions in the SSC and to make a recommendation to the CDG by early September 1985 on the clustered IR issue.

Reports Generated:

Meeting minutes

Name: "Realistic" Lattice Workshop

Leader: A. Garren, SSC/CDG

Dates: May 29-June 4, 1985, CDG/Berkeley

Members:

M. Allen
A. Chao
E. Courant
D. Douglas
A. Garren
S. Heifets
D. Johnson
B. Leemann
C. Leemann
P. Limon
Z. Parsa
S. Peggs
L. Schachinger
K. Steffen
M. Syphers

Charge:

To study the lattice issues taking into account the realistic accelerator physics and systems considerations.

Reports Generated:

Workshop report in preparation.

Name: Task Force on Commissioning and Operation of the SSC

Leader: P. Limon

Members:

W. Fowler
D. Groom
D. Hartill
F.R. Huson
C. Leemann
P. Limon
D. Lowenstein
R. Orr
P. Reardon
P. Wanderer

Name of Initiating Workshop (if any): Commissioning and Operation of SSC

Workshop Leader: P. Limon

Workshop Dates: January 14-18, 1985

Workshop Members: (see attached list)

Task Force Meetings:

February 26-27, 1985/FNAL
March 25-26, 1985/FNAL
April 12-13, 1985/CDG, Berkeley (Final Meeting)

Charge:

This task force was charged with evaluating the commissioning and operating characteristics of rings made with various types of magnets.

Reports Generated:

Interim report of the Workshop on Commissioning & Operations -- Jan. 1985
Final Task Force Report -- July 1985

PARTICIPANTS

Workshop Coordination

Don Groom	University of Utah
Peter Limon	Central Design Group
Karen Larsen	Lawrence Berkeley Laboratory

Cryogenics Group

William Fowler, Coordinator	Fermi National Accelerator Laboratory
Donald Brown	Brookhaven National Laboratory
Claus Rode	Fermi National Accelerator Laboratory
Peter VanderArend	Cryogenics Consultants, Inc.
John Van Sloan	Air Products & Chemicals, Inc.
Richard Wolgast	Lawrence Berkeley Laboratory

Design Group

Christoph Leemann, Coordinator	Lawrence Berkeley Laboratory
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Paul Reardon, Coordinator	Brookhaven National Laboratory
Phil Bryant	CERN
Lyn Evans	CERN
Mike Harrison	Fermi National Accelerator Laboratory
Russ Huson	Texas Accelerator Center
Andrew Hutton	Stanford Linear Accelerator Center
Derek Lowenstein	Brookhaven National Laboratory
Robert Mau	Fermi National Accelerator Laboratory
Rich Orr	Fermi National Accelerator Laboratory
John Poole	CERN
Luc Vos	CERN
Peter Wanderer	Brookhaven National Laboratory

Systems Group

Donald Hartill, Coordinator	Cornell University
Dixon Bogert	Fermi National Accelerator Laboratory
Richard Cassel	Stanford Linear Accelerator Center
Karl Koepke	Fermi National Accelerator Laboratory
Gerry Tool	Fermi National Accelerator Laboratory
Peter Yamin	Department of Energy
John Ziegler	Texas Accelerator Center

Name: Photo Desorption Task Force

Leader: N. Mistry (Cornell)

Members:

N. Mistry
P. Limon
H. Halama
A.G. Mathewson
G. Williams
T.S. Chan
E.L. Garwin
H. Jostlein
S. Krinsky
M. Tigner

Name of Initiating Workshop (if any): Photo Desorption at the SSC

Meetings:

August 28-29, 1984/BNL
April 28-29, 1985/Gaithersburg, MD (with additional attendees)

Charge:

To address the question of the effect of synchrotron radiation on spoiling the vacuum by desorbing the molecules frozen on the inside surface of the vacuum pipe.

Reports Generated:

Note to M. Tigner -- September 5, 1985
Proposal for experiment to NSLS - December 19, 1985 (by H. Jostlein)

Name: Power Supply and Quench Protection Task Force

Leader(s): W. Hassenzahl and D. Hartill

Members: (same as shown below in "Workshop Members")

Name of Initiating Workshop (if any): Power Supply and Quench Protection

Workshop Leader: P. Limon

Workshop Dates: April 1 - 5, 1985

Workshop Members:

G. Cottingham
D. Hartill
W. Hassenzahl
K. Koepke
H. Kraus
G. Lopez
A. Prodell
G. Tool
T. Tamanaka
J. Zeigler

Task Force Meetings: April 1 -5, 1985 / CDG, Berkeley

Charge: To investigate the power supply requirements and quench behavior of different magnet types.

Reports Generated:

Interim Workshop Note to M.Tigner from P. Limon -- April 1985

Name: Task Force on Low Temperature Operation of the SSC

Leader: M. McAshan

Members:

C. Taylor
W. Hassenzahl
S. Caspi
P. Vander Arend
W. Fowler
R. Shutt

Name of Initiating Workshop (if any): None

Meetings:

April 12, 1985/CDG, Berkeley
May 19, 1985/CDG, Berkeley
June 14, 1985/CDG, Berkeley

Charge:

Examine technical feasibility and potential cost advantages of operation at 2K. This examination is to include refrigeration schemes and magnet configurations appropriate to operation at both 6T and 8T -- all at a temperature of 2K.

Reports Generated:

"Report of the Task Force on Low Temperature Operations" slated for completion June 14, 1985.

Name: Site Parameter Document Review Panel

Leader: J. Sanford

Members:

W. Alexander
P. Livdahl
R. Matyas
R. Neal

Meeting Dates:

February 12, 1985
March 27 & 28, 1985

Attendees:

W. Murphy
A. Gursoy
P. Gilbert
W. Alexander
P. Livdahl
T. Toohig
R. Neal
V. More

Charge:

To review the SSC Siting Parameters Document that was being prepared by personnel from CER Corporation and its sub-contractor PBQ&D.

Reports Generated:

Letters to M. Tigner following the meeting on March 28, 1985.

Name: Tunneling Technology Review Panel

Meeting Date: December 9-10, 1984

Leader: R. Matyas

Name of Initiating Workshop (if any): None

Panel Members:

H. Cerruti
E. Cording
D. Hammond (Chair)
J. Hattrup
J. Lilly
J. Monsees
T. O'Rourke
F. Kulhawy (Planner)

Charge:

To review unsolicited proposal from Texas A&M Research Foundation on tunneling technology and to determine its feasibility.

Reports Generated:

Panel Report and Recommendations Received at CDG -- 12/22/84
Report to Director, CDG -- 1/5/85
Summary Report Sent to Wallenmeyer -- 1/5/85

Name: DOE Workshop on Fine Filament NbTi Strand

Leader: R. Scanlan

Members:

E. Fisk
A. Green
D. Larbalestier
R. Lundy
A. MacInturff
R. Remsbottom
R. Rocha
W. Samson
R. Scanlan (Chair)
M. Suenaga
C. Taylor
M. Tigner

Dates:

January 17, 1985
April 17-18, 1985

Charge to the Task Force: (1) To review the status of procurement of conductor and cable for the SSC, (2) to review fine filament R&D and evaluate new proposals and (3) evaluate methods for further increasing current density.

Reports Generated by the Task Force:

"SSC SC Working Group Summary" -- January 17, 1985
Meeting notes -- April 18, 1985

Name: Magnet System Test Site Task Force

Leader: R. Neal

Members:

D. Brown
P. Limon
G. Cottingham
R. Louttit
E. Willen
P. Vander Arend
D. Bogert
R. Orr
C. Rode
A. Tollestrup
G. Tool
W. Hassenzahl
F.R. Huson

Name of Initiating Workshop (if any): None

Panel Meetings:

September 13-14, 1984/SLAC
September 25, 1984/FNAL
September 26-27, 1984/BNL
October 11-12, 1984/Chicago (O'Hare)

Charge: (see attached text)

Reports generated:

Final Report, October 1984 (SSC-SR-1001)

CHARGE TO THE MAGNET SYSTEM TEST SITE TASK FORCE

Introduction

It has been anticipated that thorough testing of the proposed SSC magnet system components in a system setting will be necessary prior to construction of the SSC. In view of the relatively long lead time needed to prepare for and carry out the test, it seems appropriate to examine the question of where to carry out the test. There seems to be wide agreement that the test site can be independent of magnet style and of place of magnet manufacture. There also seems to be wide agreement that, by virtue of existing facilities and experience, BNL and FNAL are the two best candidate sites. Consequently it seems appropriate to restrict our considerations to those possibilities at this time.

In determining the most advantageous venue for the test, both cost effectiveness and availability of the needed facilities and manpower are primary factors. In assessing what facilities are needed, it is necessary to have a clear concept of the scope of the system(s) to be tested, of the types and numbers of tests to be carried out and of the likely length of time for which this initial system test facility must be available.

Report

Wanted is a report with a critical evaluation of the two potential sites with regard to availability of the needed facilities and manpower on the needed time scale and an estimate of the cost to designated SSC R/D funds of preparing each of the sites for the tests and for operating the facilities during the test period. It seems reasonable to assume that the cost of installing the magnets and other components to be tested will be relatively site independent and consequently need not be considered in the report unless this hypothesis is believed by the Task Force to be incorrect. In writing your report you should assume that adequate magnets and other components will be available early in CY 1987 and that all initial major design validation tests need to be completed in CY 1987.

This report, dealing with the technical aspects of the SSC Magnet Systems test, will be used as a major part of the input in deciding the most appropriate venue and management for these Magnet System Tests.

The Task Force Report should contain 6 major items:

1. A description of a suggested Test System(s) for each of the three magnet styles of the RDS. For example, in the case of design A it might be 5 lattice cells together with all cryogenic distribution, power supply, control and monitor equipment needed for accelerator operation or alternatively it might be two cryogenically independent groups of X cells for simultaneous testing of different features, etc., etc.

2. A description of a suggested test regimen(s) for the suggested Test System(s). For example, one might need 10^n full energy ramps at rate X Ts^{-1}, 10^m simulated beam-induced quenches, 10^p cool down-warm up cycles with interspersed magnetic, mechanical and electrical measurements, in situ magnetic field measurements, quench propagation across all boundaries, etc., etc. Estimate the time required to carry out each of the suggested major design validation tests. It seems reasonable to assume that a major system test bed facility needs to be in operation throughout Ph I and Ph II of the SSC and that it is practical and desirable to move the system test bed to the SSC construction site at the end of the first year after NTP. Criticize that assumption and the consequent conclusion that the test facilities under discussion in your report need to be available until the end of the first year after NTP even though the first round of design validation tests are to be completed at the end of 1987.

3. A description with rough specifications of the major facilities needed to carry out the suggested tests. To be included are equipment, housing needs, personnel work space, refrigeration, cryogenic distribution, power supplies, utilities and personnel and equipment safety systems. Any significant dependence of facility needs on magnet style should be described and cost differences estimated.

4. A list for both BNL and FNAL of the relevant facilities that exist and a critical evaluation of their suitability for the task at hand including a description of needed modifications, if any. Also, for both FNAL and BNL, list additional facilities that would have to be purchased or built to carry out the test program. For both potential sites estimate the cost to designated SSC R/D funds for modification of existing facilities and for bringing them into operation in readiness for the tests as well as the cost to SSC R/D funds to provide and bring into operation any additional facilities that woud be required.

5. An estimate for both sites of the manpower required to prepare the facilities for the tests and to operate the facilities during the test. The estimate shoud be broken down in terms of physicist, engineer, technician, and other manpower. Assess the availability of the needed manpower at each of the sites.

6. Discuss other technical and economic factors which may affect the cost and availability of needed resources on the needed time scale and compare the two sites with respect to these factors.

Name: Fiscal and Management Review Panel

Leader: R. Neal

Members:

T. Elioff
R. Matyas
R. Yourd

Name of Initiating Workshop (if any): None

Meetings:

October 19, 1984 / LBL
October 27, 1984 / FNAL
November 2, 1984 / BNL
November 14, 1984 / TAC
November 21, 1984 / LBL

Charge: Recommend a uniform monthly accounting and technical reporting scheme to be used by the laboratories participating in SSC Magnet R&D.

Reports generated:

Final draft of the report completed November 21, 1984.

Name: Technical Magnet Review Panel (Interim)

Leader: A. Tollestrup (Chair)

Members:

T. Elioff
F.R. Huson
P. Limon
R. Lundy
R. Neal
P. Reardon
C. Taylor
R. Watt
R. Yourd

Name of Initiating Workshop (if any): None

Meetings:

October 17-18, 1984/LBL
October 25-26, 1984/FNAL
October 31 - November 1, 1984/BNL
November 12-13, 1984/TAC
November 19-20/LBL

Charge: (1) To delineate for each design type that minimal set of technical data which are needed for the design type selection process and which can only be obtained from models and prototypes. (2) To review critically and report progress, from October 1983 to date, of each of the three major design types. (3) To review critically plans for FY 1985 in light of (1) and, as appropriate, suggest changes which may enhance their effectiveness. (4) To write a report setting forth the results of (1), (2), and (3) in a systematic fashion.

Reports Generated:

Interim Report was issued November 1984

Other information:

New panel is being re-formed. Meetings are scheduled as follows:
July 1-2, 1985/TAC
July 12 - 13/LBL
Final report due July 25, 1985

54-940 : 1986 O - 48

Name: Technical Magnet Review Panel (new)

Leader: A. Tollestrup (Chair)

Members:

F.R. Huson
R. Lundy
P. Reardon
H. Hirabayashi
C. Taylor
R. Watt
R. Yourd

Name of Initiating Workshop (if any): None

Meetings:

July 1 - 2, 1985/TAC
July 12 - 13, 1985/LBL

Charge: (1) Review magnet and cable development programs at BNL, FNAL, LBL and TAC. (2) Write a report evaluating the technical status of dipole and quadrupole magnet design and development work for the 1 in 1 and 2 in 1 low and high field magnet styles. For each style enumerate the R/D remaining before each style can prudently be carried to the full scale prototype stage. This enumeration should include an estimate of the time and manpower effort needed to complete the pre-prototype R/D. The report should include a detailed account of model tests for the various designs. (3) Evaluate and report on the status of superconducting cable development and enumerate further development objectives which could reasonably be expected to be complete in time to have a beneficial impact on SSC magnet cost, reliability and ease of operation. The report should be complete by July 25, 1985.

Reports Generated:

Final Report due July 25, 1985

Name: **Magnet Selection Advisory Panel**

Leader: **F. Sciulli**

Members: **(see attached list)**

Name of Initiating Workshop (if any): **None**

Meetings: **Scheduled for August 25-30, 1985.**

Charge: **(see attached text)**

Reports Generated: **None to date.**

MAGNET SELECTION ADVISORY PANEL

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CHARGE TO THE MAGNET SELECTION ADVISORY PANEL

A number of Basic Magnet Types have been considered for possible SSC service. They include mechanically linked dual aperture magnets which may or may not be thermally or magnetically linked (2-in-1) and mechanically, magnetically and thermally independent single aperture magnets (1-in-1). Both high field (6T or more) and low field (about 3T) versions of these types have been studied and developed to a greater or lesser extent. After considerable study of the many possible combinations, five have emerged as most likely to provide economical and reliable options of the SSC. These five are: I. a low field, mechanically and thermally linked, magnetically independent 2-in-1 type; II. a high field, mechanically, thermally and magnetically linked 2-in-1 type; III. a high field 1-in-1 type with cold iron; IV. a low field 1-in-1 type; V. a high field, warm iron 1-in-1 type.

During the last quarter of Fiscal Year 1985, one of these Basic Magnet Types will be selected for final prototype development by the Director of the Central Design Group. In aid of this selection the Advisory Panel will submit a report to the Director containing the Panel's recommendation in the form of an ordered list of these five Basic Magnet Styles. The rationale for this recommendation shoud be given in detail. If no clear choice emerges this sould be clearly stated and justified.

In making its recommendation the Advisory Panel will be guided by the Criteria set forth below, using technical materials supplied by the CDG and such other technical inputs as it may solicit at its discretion.

The report of the Advisory Panel is due by September 1, 1985.

Criteria

In its deliberations the Panel will consider the SSC to be a hadron collider designed ultimately to achieve 20 TeV per beam at a luminosity of $10^{33}\text{cm}^{-2}\text{sec}^{-1}$.

In rendering its judgement the Advisory Panel should consider the general implications of low field and high field and 1-in-1 and 2-in-1 features, as well as details of proposed mechanical, thermal and magnetic designs. Both system features and characteristics of the magnets considered as individual components need to be taken into account. While the dipoles are the major cost component of the magnet system, the quadrupoles and various correctors inherent to the various Basic Magnet Types must receive due consideration.

The Criteria to be used in making an overall recommendation are:

1. Relative capital cost of an SSC facility employing a particular Basic Magnet Design.
2. Workability of the Basic Designs presented.
3. Complexity of the overall magnet system inherent to the particular Basic Design.
4. Operational complexity of an SSC employing the particular Basic Design.
5. Relative flexibility of an SSC design employing the particular Basic Design.
6. Likely impact of the Basic Magnet Design on the SSC construction schedule.
7. R/D time and effort needed to develop the Basic Design.
8. Accelerator Physics considerations.
9. Other considerations deemed appropriate by the Advisory Panel.

Comments on the Criteria (Numbers below refer to the list above)

1. Cost figures will be developed by the CDG with input from the SSC R/D participants and from independent commercial firms experienced in manufacturing superconducting magnets. In calculating the overall SSC facility cost, the conventional construction costs developed by the CDG and its A/E consultants will be used. The Reference Designs Study will be a primary reference. In computing magnet costs, the CDG will select the aperture to be used with each Basic Magnet Type based on accelerator physics considerations and the best information available on the likely field errors for each Basic Magnet Type.

2. Workability or practicality refers to the manufacturability and potential reliability of a particular design, taking into account needed tolerances, material specifications and assembly procedures. Model tests by the developers will provide concrete evidence in this area.

5. Relative flexibility is with regard to: a) possibilities for staging the SSC to speed up first physics use while reducing spending rates if necessary; b) operations such as injection, beam adjustments during collision, repair of magnets; c) concommitant site restrictions.

6. Particular impacts might be lengthened construction time for larger circumference, needs for special portals or on-site factory facilities for particular magnet designs, duration of manufacturing time for various magnets.

8. Accelerator Physics issues would have to do with inherent properties of low and high field rings and coupled or uncoupled beam channels. One would expect vacuum chamber impedance, surveying, magnet shuffling, radiation protection and other considerations to play a role.

Information to be Supplied by the CDG to the Advisory Panel

1. Report of the CDG Cost Estimating Task Force.
2. Report of the Task Force on Operations and Commissioning.
3. Report of the Aperture Task Force.
4. Drawings, specifications and model test results, where available, representing the current state of development of each of the Basic Magnet types.
5. Report of the Technical Magnet Review Panel.

Name: Cost Estimating Task Force

Leader(s): T. Elioff & R. Yourd (co-chairs)

Members:

K. Mirk
C. Goodzeit

Consultants:

J. Carson
N. Engler
F.R. Huson
W. Schneider
E. Kelly
General Dynamics (R. Baldi)
Westinghouse (L. Young)

Name of Initiating Workshop (if any): None

Meetings: Tentatively scheduled for July and August 1985.

Charge: To perform a detailed review of costs for all magnet design styles for the SSC.

Reports Generated: None to date.

Name: Business Affairs and Management Advisory Panel

Leader: R. Matyas

Members:

H. Doney
F. Mattmueller
R. Williams
J.D. Jackson, Ex Officio Member
D.P. Kreitz, Ex Officio Member

Name of Initiating Workshop (if any): None

Meeting Dates:

March 15, 1985/URA, Washington, D.C.
April 11-12, 1985/CDG, Berkeley
May 29, 1985/Cornell University, Ithaca

Charge:

To advise and assist the CDG Directorate on establishing a framework for independent operations at the permanent site, utilizing state-of-the-art methods, equipment, and procedures. The desirable timetable would have the CDG capable of independent operations not later than September 30, 1986.

Reports Generated:

Interim Report due to CDG Director -- June 1985
Final Report due -- December 1985

Name: Task Force on Detector R&D for the SSC

Leader: M.D.G. Gilchriese

Members:

B. Cox
M.D.G. Gilchriese
H. Gordon
P. Grannis
D. Hartill
J. Jaros
P. Kunz
S.C. Loken
D. Nygren
A. Seiden
M. Shochet
F. Paige

Name of Initiating Workshop (if any): None

Meetings:

May 9, 1985/FNAL
May 19, 1985/SLAC

Charge to the Task Force: (see attached text)

Reports Generated:

Preliminary Report, May 23, 1985

May 1, 1985

Charge to the Task Force on Detector R&D for the SSC

The Task Force will advise on the detector R&D needed to assure the timely construction of detectors capable of exploiting the luminosity and energy of the SSC at turn-on. In addition, the Task Force should estimate the manpower requirements, costs, and time scale of this R&D. The Task Force should also recommend the procedures to be followed to accomplish the tasks.

1. There should be a preliminary report on the R/D objectives, manpower requirements, costs, and time scale in time for the May 24 HEPAP working group meeting at SLAC. If there are particularly pressing problems needing funding in FY86, these should be identified for HEPAP.

2. It is expected that some part of the 1986 Snowmass Summer Study will be devoted to detector problems. The Task Force is requested to provide recommendations on the optimum way to structure this effort.

3. Finally, recommendations are requested regarding the scope and costs of the SSC detector R&D to be done in FY87.

4. What role, if any, should the SSC Central Design Group play in facilitating this detector R&D?

APPENDIX B.

REPORTS

APPENDIX B1. CDG REPORTS

Number	Date	Author	Title
SSC-1	10/84	T. Elioff	Monthly Report Oct.-Nov. 1984
SSC-2	11/84	A. Chao	SSC Aperture Workshop Summary
SSC-3	12/84	J. Peterson	Aperture Task Force Report
SSC-4	1/85	T. Elioff	Monthly Report - Dec. 1984
SSC-5	1/85	P. Limon	Workshop on SSC Commissioning and Operations
SSC-6	1/85	M. Furman	Simple Method to Symplectify Matrices
SSC-7	2/85	J. Peterson et al.	Magnetic Errors in SSC
SSC-8	2/85	D. Douglas	Interpolation of Off-Energy Matrices
SSC-9	2/85	D. Douglas	Options to Make PATRICIA Symplectic
SSC-10	2/85	T. Elioff	Monthly Report - Jan. 1985
SSC-11	2/85	J. Peterson	Aperture Task Force Report
SSC-12	2/85	J. Sanford	Scope of Work for A/E Services
SSC-13	3/85	T. Elioff	Monthly Report - Feb. 1985
SSC-14	3/85	S. Myers	Overlap Knock-Out Resonances in the SSC
SSC-15	4/85	J. Sanford	Site Parameters Document
SSC-16	4/11/85	A. Chao C.W. Leemann	More on the Overlap Knockout Resonances in the SSC
SSC-17	4/12/85	A. Chao J. Peterson	Eddy Current in the SSC
SSC-18 LBL-18903(3)	4/85	D. Douglas E. Forest	A Method to Render Second Order Beam Optics Programs Sympletic
SSC-19	4/85	E. D. Courant D. R. Douglas A. A. Garren D. E. Johnson	SSC Test Lattices
SSC-20	4/85	S. Peggs M. Furman A. Chao	A Possible Screening Procedure for Random Multipole Field Errors Before Tracking Studies
SSC-21	4/85	S. Heifets	Random Sextupoles in the SSC Lattice
SSC-22	4/22/85	D. Edwards	Aperture Task Force Interim Report - Aperture Criterion Group
SSC-23	5/85	D. Douglas	Ion Stability in Bunched Electron Beams
SSC-24	5/85	B. T. Leemann D. R. Douglas E. Forest	Tracking the SSC Test Lattices
SSC-25	5/85	J. Bisognano	Collective Effects and the Design of the SSC

Number	Date	Author	Title
SSC-26	4/85	T. L. Collins	On Choosing an Aperture
SSC-27	4/19/85	M. Harrison	Tevatron Operational Experience and Implications for SSC Aperture
SSC-28	4/85	M. Furman A. Chao	Effect of Long Range Beam-Beam Interactions on the Stability of Coherent Dipole Motion
SSC-29	4/85	E. Forest	Normal Form Algorithm on Non-Linear Symplectic Maps
SSC-30	4/85	E. Forest	Equivalence of Michelotti's Normal Form and the Map Normal Form as Used By the MARYLIE Code
SSC-31	5/85	A. Chao	Accelerator Physics Studies for the SSC
SSC-32	5/85	E. Forest	Algebraic Theory of Beam-Beam Interactions in the Lens Model
SSC-33	5/85	M. Tigner	Where Is the SSC?
SSC-34	5/85	J. R. Sanford	Civil Systems Aspects of the SSC
SSC-35	5/85	P. Limon	Accelerator Systems of tne SSC
SSC-36	5/85	S. Peggs	The Dependence of Single Particle Stability on Net Chromaticity in CESR, Near $Q_h = 9 + 1/3$
SSC-37	3/85	T. Elioff	Monthly Report - March 1985
SSC-38	4/85	T. Elioff	Monthly Report - April 1985
SSC-39	5/85	T. Elioff	Monthly Report - May 1985
SSC-40	6/85	K. Steffen	Preliminary Lattice Proposal for Polarized Beam Acceleration in SSC

SSC Special Reports

Number	Date	Author	Title
SSC-SR-1001	10/84	W. Hassenzahl	Report of the Task Force on SSC Magnet System Test Site
SSC-SR-1002	3/85	T. Elioff	Program Plan
SSC-SR-1003	3/85	T. Elioff	Management Plan
SSC-SR-1004	4/1/85	R. Yourd et al.	SSC Reference Design Magnets Style "D" Cost Design
SSC-SR-1005	4/15/85	D. Groom et al.	Report of the Task Force on SSC Commissioning and Operations
SSC-SR-1006	7/1/85	W. Hassenzahl et al.	Report of the Task Force on Quench Protection and Power Supply Operation A. Quench Protection B. Power Supply Operation
SSC-SR-1007	6/25/85	M. McAshan et al.	2 K Magnet Operation Task Force Report
SSC-SR-1008	4/7/85	A. D. Krisch	Proceedings of the Meetings on the

UM HE 85-08		et al.	SSC Between Representatives of Industry and High Energy Physics Held at the University of Michigan on December 6, 1984, and January 7, 1985
SSC-SR-1009	5/23/85	G. Gilchriese et al.	Preliminary Report from the Task Force on Detector R&D for the SSC

SSC Notes

Number	Date	Author	Title
SSC-N-1	4/18/85	T. E. Toohig	Land and Shielding Requirements from the HEB: Impact of Conventional Facilities
SSC-N-2	3/85	T. E. Toohig	SSC Relative and Comparative Tunnel Costs
TM-1299 SSC-N-3	4/23/85	T. E. Toohig	Notes from a Telephone Conversation with John Elias: Radiation Levels in the Tevatron Tunnel
SSC-N-4 TM-1306	4/22/85	T. E. Toohig	Field- and Energy-Independent Normalization of the SSC Collider Ring Costs
SSC-N-5	4/85	J. Peterson	SSC Aperture Task Force Coordination Meeting, 24 April 85 at CDG/LBL
SSC-N-6	4/22/85	T. E. Toohig	Land Acquisition Requirements for the SSC
SSC-N-7	3/28/85	J. Peterson A. Chao	How Much Error in Circumference Difference Between The Two Rings Can We Tolerate?
SSC-N-8 TM-1289	11/23/84	T. E. Toohig	Observations on LEP with a View to SSC
SSC-N-9	5/15/85	T. E. Toohig	Magnet Length and Conventional Facilities
SSC-N-10	4/85	J. D. Cossairt	Design Considerations for Personnel Access Penetrations for the SSC
SSC-N-11	5/21/85	S. Marks J. Peterson	Memo on Error Analysis of Superferric Magnet
SSC-N-12 TM-1316	6/24/85	K. Koepke	A Simulation of Quenches in SSC Magnets with Passive Quench Protection
SSC-N-13	6/28/85	D. Neuffer	First Estimataes of Allowable Field Non-Linearities

APPENDIX B2. BNL REPORTS

SSC Technical Note Number	Date	Author	Title
1	7/20/83	M. Barton	Possible Use of Window Frame Magnets for SSC
2	9/9/83	M. Puglisi	The SSC Resonant Cavity Design Criteria
3	10/10/83	J.G. Cottingham	Accelerating the Quench Propagation in Long SSC Magnets
4	10/10/83	R.C. Fernow	Coil Design for the Prototype SSC Dipole
5	10/26/83	G. Parzen	Random Error Field Multipoles in SSC Magnets
6	11/16/83	R. LeRoy	Finie Element Analysis of SSC Prototype Clamping Shell
7	12/20/83	S.R. Plate	The Case of the Missing Pole Piece Laminations
8	1/13/84	H.J. Halama	Ann Arbor SSC Workshop Summary Report on Vacuum System, Ann Arbor, Mich. Dec. 11-17, 1983
9	2/6/84	D.P. Brown	The Case of Hot Tin Magnets
10	2/27/84	A. Ghosh W.B. Sampson G. Stenby A.J. Stevens	Radiation Exposure of Bypass Dipoles
11	2/24/84	A.F. Greene H.G. Kirk	Differences in Harmonics for Concave and Convex-Wound CBA Coils
12	3/21/84	G. Ganetis A.J. Stevens	Results of Quench Protection Experiment
13	4/18/84	E.H. Willen	SSC Magnets with Niobium-Tin
14	5/17/84	R. Fernow G. Morgan	Coil Design for the LBL-SSC Prototype Dipole (SSC-B61)
15	5/30/84	R.I. Louttit	Comparison of Heat Loads CBA-SSC
16	6/21/84	E.D. Courant	Chromaticity Adjustment in SYNCH Program
17	7/27/84	G. Morgan	Calculation of Superconductor Magnetization Effects in Magnets Using GFUN
18	8/29/84	J.C. Herrera	Characteristics of an SSC (pp) (Transparencies for U.S. 1984 High Energy Particle Accelerator School held at Fermilab, August, 1984)
19	10/8/84	R.C. Fernow G.H. Morgan	Coil Design for the 40 mm Collared SSC Dipole (SSC-C5)
20	10/30/84	H.J. Halama	Some Comments on the SSC Bore Tube
21	11/8/84	D.P. Brown K.C. Wu	Cooldown Calculations for SSC Magnets

SSC Technical Note Number	Date	Author	Title
22	1/29/85	D.C. Wu	Low Temperature Heat Shield for the SSC Magnet Type D
23	2/12/85	G.H. Morgan	The 1-in-1 SSC Dipole with C5 Coils
24	3/13/85	D. Brown	Cryogenic Operational Implications of Cyrogenically-Coupled Magnets
25	3/13/85	K.C. Wu	Recoolers for the SSC Reference Design D

APPENDIX B3. FERMILAB REPORTS

Number	Date	Author	Title
TM-1213	9/15/83	F.R. Huson	20 TeV Colliding Beam Facilities
TM-1214	9/21/83	F.R Huson	Potential 20 TeV Site in Illinois
TM-1232	11/83	S.C. Snowdon	Combined Function Magnets Profile Design
TM-1239	1/84	K.Y. Ng	An Estimate of the Longitudinal and Transverse Impedances for the Superconducting Super Collider
TM-1246	2/84	S. Ohnuma	How Much Random Sextupole Field Can We Have in the Presence of Beam-Beam Interactions?
TM-1247	3/84	S. Ohnuma	Width of Non-Linear Resonance
TM-1249	3/84	E.A. Treadwell	Pumping Rates for Water Drainage in the Main Ring Tunnel: Scale Considerations of the SSC
TM-1260	7/83	R.R. Wilson	A Tevatron Improvement Program
TM-1285	11/84	J. O'Meara	Water Cooling Considerations for the SSC
TM-1289	11/84	T.E. Toohig	Observations on LEP with a View to SSC
TM-1292	12/84	T.E. Toohig SSC Study Group	A Preliminary Design for a 20 TeV Collider in a Deep Tunnel at Fermilab
TM-1294	1/85	B.C. Brown	A Naive Comment on Changing SSC Persistent Current Sextupole Thru Metallurgical Changes in the Superconductor
TM-1299	3/85	T.E. Toohig	SSC Relative and Comparative Tunnel Costs
TM-1300	3/85	A.D. McInturff	An Aperture Study
TM-1306	3/85	T.E. Toohig	Field-Independent Normalization of SSC Collider Ring Costs
FN-396	1/84	R.P. Johnson	The Tevatron as an SSC Prototype: Experience Versus Predictions
FN-440	4/84	Jorge Morfin	Leptoproduction at an SSC Fixed Target Facility
Conf-85/14	1/85	S. Loken J.G. Morfin	A Fixed Target Facility at the SSC
Conf-85/15	1/85	J.G. Morfin J.F. Owens	Measuring Structure Functions at SSC Energies
Conf-85/33	2/85	B. Cox F.J. Gilman	Standard Electroweak Interactions and Higgs Bosons

APPENDIX 04. LBL REPORTS

Number	Date	Author	Title
SSC Note-1 LBL-16034	8/83	A. Garren	20 TeV Collider Lattices with Low-B Insertions
SSC Note-2	9/83	A. Garren M. Cornacchia F. Dell	Chromatic Properties and Tracking Studies of a 20 TeV pp Collider
SC Note-3 LBID-795	9/83	C. Leemann	Beam-Beam Tune Shift for Bunched Beams Crossing at an Angle
SSC Note-4 LBID-796	9/83	M. Cornacchia	Discussion on the Choice of Working Point for s Six-Fold SSC Lattice
SSC Note-5 LBID-797	9/83	A. Garren	6.5 Tesla SSC Lattice
SSC Note-6 LBID-802	10/83	A. Garren	5 Tesla SSC Lattice - Approximate Parameters
SSC Note-7 LBID-809	11/83	D. Douglas	TABLOT and NUPLOT, Two Graphics Programs for Tune Computations
SSC Note-8 LBID-811	10/83	L. Smith	Non-Linear Stop Bandwidths
SSC Note-9 LBL-16019	8/83	E.R. Close D.R. Douglas R.C. Sah	Survey and Alignment for a 20-TeV on 20 TeV Collider
SSC Note-10 LBID-810	11/83	M. Cornacchia	Estimates of Some Tracking and Stability Requirements in the SSC
SSC Note-11 LBID-827	12/83	B. Leemann	A Fast Extraction System for the 6.5 Tesla SSC Lattice
SSC Note-12 LBL-17020	12/83	D. Douglas	Tune Shift Due to Systematic Errors in Bend Magnets
SSC Note-13 LBID-833		C. Leemann	Beam-Beam Forces for "Non-Round" Beams and Multipole Expansion of Long Range Forces
SSC Note-14 LBID-834		C. Leemann	Control of IP, Estimate of Tolerances
SSC Note-15 LBID-836	11/83	M.S. Zisman M. Cornacchia	Preliminary Design Implications of SSC
SSC Note-16 LBL-17052	12/83	C. Leemann	Choice of IP Geometry and Beam Parameters for the SSC
SSC Note-17 LBL-17253	1/84	R. Ruth	Single Bunch Instabilities in an SSC
SSC Note-18 LBL-17233	1/84	M. Puglisi	Preliminary Considerations on an RF System for an SSC
SSC Note-19 LBL-17234	1/84	M. Puglisi	Coaxial Cavity Parameters Evaluation

Number	Date	Author	Title
SSC Note-20 LBID-869		D.B. Hopkins M. Puglisi	Design Considerations for SSC RF Cavities
SSC Note-21 LBL-17254	1/84	B.T. Leemann	Injection, Extraction and Beam Abort System for the SSC
SSC Note-22 LBL-17260	1/84	M. Zisman et al	SSC Closed-Orbit Correction
SSC Note-23 LBID-874	5/85	M. Cornacchia	Discussion of Some Sextupolar Effects of Persistent Currents in the SSC
SSC Note-24 LBL-17283	1/84	A. Garren	A 6.5 Tesla SSC Lattice Example
SSC Note-25 LBID-911	6/84	D. Douglas	The Collins' Scheme for the Local Correction of Chromatic Abberations Due to Insertion
SSC Note-26 LBL-17805	1/84	C. Leemann	Considerations Regarding the Choice of Beam Parameters and IP Configurations for the SSC
SSC Note-27 LBID-912	4/84	P.D. Meyers	SSC Magnet Alignment and Aperture
SSC Note-28	10/84	D. Douglas R. Servranckx	A Method to Render Second Order Beam Optics Programs Symplectic
SSC Note-29 LBL-16026	6/84	M.S. Zisman	Preliminary Design Implications of SSC Fixed-Target Operation

APPENDIX B5. TAC REPORTS

Number	Date	Author	Title
	5/85	E. Zaidman et al D. Neuffer	Study of the Plasma Fiber Accelerator
	5/85	S. Heifits et al	Beam Tracking and Stability Analysis for the SSC
	5/85	S. Heifits D. Neuffer	Lattices for the Superferric Super Collider
	5/85	S. Pissanetzky Wm. Schmidt	Design of the Dipole Magnet for the "C" Version of the Superconducting Supercollider 20 TeV Twin-Beam
	5/85	P. McIntyre D. Neuffer Wm. Schmidt	The Three Ring Circus
	5/85	F.R. Huson et al	Superferric Magnet Option for the SSC

Appendix C

Industrial Involvement

APPENDIX C.

Industrial Involvement in SSC R&D

Industrial participation and interest in the SSC in its R&D phase ranges from expressions of eventual interest once the project is approved through detailed inquires into possible participation in the R&D efforts to actual involvement as a contractor or supplier of components or materials. Summarizing such diversity is difficult. No thoughtful analysis has yet been attempted to gauge the level of overall interest or to determine (apart from the obvious) those sectors of private industry most likely to have eventual involvement.

The existing facts are listed below in the following order:

1. Superconducting Magnet Technology
    (a) Superconducting strand and cable
        (i) Suppliers
        (ii) Possible participants
    (b) Suppliers of magnet components
    (c) Suppliers of cryostat components
    (d) Suppliers of tooling

2. Large Electrical Equipment

3. Meetings, Congresses, and Conventions

4. Architecture and Engineering
    (a) Present contractors
    (b) Respondents to the CBD Announcement for A/E Work

1. SUPERCONDUCTING MAGNET TECHNOLOGY

(a) Superconducting Strand and Cable

(i) Suppliers

Amax Specialty Metals Corporation
Refractory Division
460 Jay Street
Coldwater, Michigan 49036
(Subcontractor for extrusion of superconductor billets)

Intermagnetics General Corporation
1875 Thomaston Avenue
Waterbury, CT 06704
(Wire procurement and superconductor R&D)

New England Electric Wire Corp.
Lisbon, NH 03585
(Cable manufacturing and development)

Oxford Superconducting Technology
600 Milik Street
Carteret, NJ 07008
(Wire procurement)

RMI Company
P.O. Box 574
Ashtabulah, OH 44104
(Subcontractor for extrusion of superconductor billets)

Small Tube Products
P.O. Box 1674
Altoona, PA 16603
(Subcontractor for copper components for superconductor billets)

Supercon, Inc.
830 Boston Turnpike Road
Shrewsbury, MA 01545
(Wire procurement and superconductor R&D)

Teledyne Wah Chang
P.O. Box 460
Albany, OR 97321
(NbTi alloy procurement)

(ii) Possible participation

BBC Brown Boveri & Company, Ltd.
Oerlikon Works, P.O. Box 8242
8050 Zurich, Switzerland
(Submission of proposals for cable manufacturing)

The Furukawa Electric CO., Ltd.
9-15, 2-chome, Futaba
Shinagawa-ku
Tokyo 142, Japan
(Manufacturing of wire samples for evaluation)

Hitachi Cable, Ltd.
Tsuchiura Works
3550 Kidamari-cho
Tsuchiura-shi
Ibaraki-ken 300, Japan
(manufacturing of wire samples for evaluation)

Kawecki-Berylco, Inc.
Division of Cabot Corporation
Box 1462
Reading, PA 19603
(Prospective manufacturer of NbTi alloy)

LDM
Postbus 42
Drunen, Holland
(Potential source of hydrostatic extrusion services)

Magnet Corporation of America
197 Bear Hill Road
Waltham, MA 02254
(manufacturing of wire samples for evaluation)

National Standard CO., Ltd.
Arran Road, North Muirton
Perth, Scotland
(Potential source of hydrostatic extrusion services)

Outokumpu OY
Copper Products Division
SF-28100 Pori, Finland
(inquiry about participation)

Vacuumschmelze GMBH
Postfach 2253
Gruner Weg 37
6450 Hanau 1, West Germany
(manufacturing of wire samples for evaluation)

(b) Suppliers of Magnet Components

Active Fabricators
7850 Quincy St.
Willowbrook, IL 605521
(Kapton channel or caps for coil insulation.)

Advance Electrical Sales
1661 Industrial Way
Belmont, CA 94002

Advance Manufacturing Group
Multiwire Division
Kollmorgen Corp.
10 Andrews Road
Hicksville, NY 11801
(Application of syperconducting wire for trim coils to plastic sheet)

Alpha Products, Inc.
5570-T W. 70th Place
Chicago, ILL 60638
(Lamination Stamping)

American Metals Services
P.O. Box 250
Miami, Fla 33152
(Suppliers of Aluminum for AL Collars)

Armco Steel
Middletown, OH 45043

Armco Steel
575 Valley Forge Plaza
1150 First Avenue
King of Prussia, PA 19406
(Nitronic 40 stainless steel for collars; low carbon steel for yokes.)

Beacon Chemical CO.,
125 Mac Questen Pkwy. So.
Mt. Vernon, NY 10550
(Epoxy for assembly of yoke laminations)

Chicago Fineblanking Corp.
2068 Foster Ave.
Wheeling, Ill 60090
(Fineblanking)

Comanche Steel
805 Hannah Ave.
Forest Park, ILL
(Steel strips)

Copper & Brass Sales
415 State Parkway
Schaumburg, ILL 60196
(Suppliers of Copper & Aluminum)

Dek Plastics
3480 Swenson St.
St. Charles, Ill 60174
(RX-630 Molding)

E.H. Canis & Sons
400 Oser Avenue
Hauppaguge, NY 11787
(Kapton tape, shrink tubing, Teflon film)

Eason & Waller
2214 W. Palm Lane
Phoenix, Ariz 85009
(4 Axis G-10 Machining)

E.I. DuPont de Nemours & CO
Wilmington, Delaware 19898
(Kapton film for coil insulation.)

Essex (United Technologies)
P.O. Box 1510
Fort Wayne, Ind 46801
(Materials slitting, Superinsulation Blankets,
Kapton for Dry Windings and Magnet Wire)

General Electric CO.
1310 W. 22nd St. Suite 1107
Oakbrook, ILL 60521
(Kapton for Dry Winding)

General Electric CO.
Motor Magnet Wire Operation
Bldg. 109
Schenectady, N.Y. 12345
(Kapton)

H & J Tool & Die CO.
1565 Ocean Avenue
Bohemia, NY 11716
(Die stamping of collar and yoke laminations)

Imperial Plastics Ltd.
2611 S. 21st Ave.
Broadview, Ill 60153
(RX-630 Molding)

Joseph T. Ryerson & Son, Inc.
16th & Rockwell Sts. Box 8000-A
Chicago, IL 60680
(Steel suppliers & fabricators, Alum. suppliers)

LTV Steel
Two Continental Towers
1701 Gold Road - Suite 600
Rolling Meadows, IL 60006-4275
(Suppliers of Low Carbon & Stainless Steels)

3M
225-4N-05 3M Center
St. Paul, Minn 55144-1000
(B-Staged Kapton for Dry Winding)

Metalstamp Inc.
305 Earl Street
Shorewood, ILL 60436
(EDM Magnet End Plates)

MS Tool CO.
115 Elizabeth Dr.
Arlington Hts., IL 60005
(Experimental Parts)

Northern States Metal Corp.
51 N. Main St., Box 666-U
W. Hartford, CT. 06107
(Extrusions)

Permacil
650 Woodfield Dr., Suit 210
Schaumburg, IL 60195
(B-Staged Kapton for Dry Winding)

Phelps-Dodge
941 N. Plumgrove Rd.
Schaumberg, IL 60195
(Copper Wedges)

Plainfield Tool & Eng. Inc.
P.O. Box 326
10 East Main St. Rt. 126
Plainfield, IL 60544
(Laminations)

Raynor, Inc.
P.O. Box 458
Westminster, MA 01473
(Yoke half-shells)

Reichhold Chemicals Inc.
8420 Fawncrest Place
Ft. Wayne, Ind 46815
(Molding Compounds)

Rogers Corp.
2001 W. Williams Field Rd.
Chandler, AZ 85224
(B-Stage Kapton Molding Compounds)

Rummel Fibre
82 Progress St.
Union, N.J. 07083
(G-10 Tubing)

Shaped Wire Inc.
3655 Illinois Ave.
St. Charles, IL 60174
(Copper Wedges & SS Keys)

Spaulding Fibre
1300 So. 7th St.
DeKalb, IL 60015
(Suppliers of G-10 Tubing)

Tempel
5990 W. Touhy Ave.
Niles, IL 60648
(Lam. Stamping House)

Ullrich Copper
2 Mark Rd.
Kenilworth, N.J. 07033
(Copper Wedge Extrusions)

Wagner Fineblanking
4611 N. 32nd St.
Milwaukee, Wi 53209
(Fineblanking)

(c) Suppliers of Cryostat Components

Aluminum Company of American (Alcoa)
P.O. Box 7500
Lafayette, Indiana 47903-7500
(Alum. Extrusions)

ARMCO
333 N. 6th St.
St. Charles, Ill. 60174
(Fiberglass Post Fabrication)

Bloomer-Fiske CO.
2300 W. 47th St.
Chicago, Ill. 60609
(Steel Forming & Rolling)

Calflex
26111 Evergreen Suite 220
Southfield, Mi. 48076
(Bellows Manufacturers)

Cryogenic Consultants, Inc.
1176 North Irving Street
Allentown, PA 18103

Cryolab
4175 Santa Fe Road
San Luis Obispo, CA 93401

C.V.I., Incorporated
P.O. Box 2138
Columbus, OH 43219

E/M Lubricants, Inc.
P.O. Box 2200, Highway 52 N.W.
West Lafayette, Ind. 47906
(SSC Post Thread Lub.)

Essex (United Technologies)
P.O. Box 1510
Fort Wayne, Inc. 46801
(Materials slitting,
Superinsulation Blankets,
Kapton for Dry Winding
and Magnet Wire)

Flexonics Inc.
300 East Devon Ave.
Bartlett, Ill. 60103
(S.S. Bellows)

Gardner Products
254 N. Water St.
Batavia, Ill. 60510
(SS Thin Shields)

G.E. Mathis CO.
6102 S. Oak Park Ave.
Chicago, Ill. 60638
(Bump Forming 20' Vacuum Vessels)

Ideal Tool
5615 S. Claremont
Chicago, Ill. 60636
(Planing of vacuum vessel,
heavy machining)

Medco
340 E. Howard St.
Des Plaines, Ill. 60018
(4 Axis Machines,
G-10 Machining, Flanges)

Metal Bellows
1075 Providence Highway
Sharon, Ma. 02067
(S.S. Bellows)

Metal Fab Corp.
P.O. Box 2611
Ormond Beach, Fl. 32075
(Bellows Manufacturers)

Metal Lab
7316 Durand Ave.
Sturtevant, Wi. 53177
(Vacuum Degassing)

Metalized Products
73 East St.
Winchester, Mass. 01890
(Superinsulation Suppliers)

Nicofibers
Ironpoint Road
Shawnee, Ohio 43782
(Fiberglass Separator for
Insulation Blankets)

Plymouth Tube
P.O. Box 11
Winfield, Ill. 60190
(SS Extrusions)

Precision Extrusions
727 East Green Street
Bensenville, Il. 60106
(Mfr. of Extrusions &
Alum. Tubing)

Ultra Specialties
1360 Howard St.
Elk Grove Village, Ill. 60007
(General Machine & Fab.)

Walco Tool
P.O. Box 220B R.R. #3
Lockport, Ill. 60441
(General Machine & Fab.)

Western Pneumatic
P.O. Box W
Kirkland, Wa
(Tube Mfr.)

(d) Suppliers of Tooling

American Grinding
2000 N. Mango
Chicago, Ill. 60639
(Collaring Press,
Ground ready made tables)

Danco Tool
Wheatland & Mellon Sts.
Phoenixville, Pa 19460
(Diemakers & Lamination
Stamping House)

DeKalb Precision
2031 Sycamore Rd.
DeKalb, Ill. 60115
(General Machine & Fab.)

K.C. Glader
6056 Gross Point Rd.
Chicago, Ill.
(Close Tol. Stl. Strip)

Lesco Tool and Die
1929 Miller Street
P.O. Box 8096
Houston, TX 77288

Meyer Tool and Mfg., Inc.
9221 South Kilpatrick
Oak Lawn, IL 60453

Numerical Precision Inc.
2200 Foster Ave.
Wheeling, Ill. 60090
(4 Axis Mills)

2. LARGE ELECTRIC EQUIPMENT

Firms interested in large scale involvement in the SSC project (some already involved modestly):

Ansaldo spa
Via A. Pacinotti 20
16151 Genova, Italy
(Inquiry about magnet manufacturing)

BBC Brown, Boveri, Inc.
1460 Livingston Avenue
North Brunswick, N.J. 08902
(Inquiry about magnet manufacturing)

Brown, Boveri & Cie
Postfach 351, GK/MS 3
6800 Mannheim 1, West Germany
(Participation in manufacturing plan and
cost estimates; inquiry about magnet manufacturing
in the U.S.)

General Dynamics
(Magnet construction for TAC; cryostat
development with LBL; cost estimates
for SSC-CDG)

Hitachi Works, Hitachi Ltd.
3-1-1 Saiwai-cho
Hitachi-shi
Ibaraki-ken, Japan
(Inquiry about magnet manufacturing)

Toshiba Corporation
1-6, Uchisaiwai-cho
1-chome, Chiyoda-ku
Tokyo 100, Japan
(Inquiry about magnet manufacturing;
starting assembly of model magnets)

Westinghouse
(Cost estimates for SSC-CDG)

3. MEETINGS, CONGRESSES AND CONVENTIONS OF INDUSTRIAL CORPORATIONS INTERESTED IN SSC TECHNOLOGICAL DEVELOPMENT AND NEEDS

(a) 5th Annual Meeting, Fermilab Industrial Affiliates, May 21-22, 1985. Attended by 70 participants. A listing of these participants is available on request.

(b) Intense Briefing on Large Scale Superconducting Magnet Technology, Fermilab, February 19-20, 1985. This briefing was attended by 38 participants. A complete list of these participants is available on request.

4. ARCHITECTURE AND ENGINEERING

(a) Present Contractors

CER Corporation
2225 East Flamingo
Suite 300
Las Vegas, Nevada 89109
($320 K, 6 months)

RTK
Joint Venture
1800 Harrison Street
Oakland, CA 94623-2321
(expected to be approximately
$6M, 2-1/2 years)

(b) Respondents to CBD Announcement for A/E Work

Parsons, Brinckerhoff, Quade & Douglas, Inc.
1625 Van Ness Avenue, 4th Floor
San Francisco, CA 94109-3678

Ralph Parsons CO.
100 W. Walnut Street
Pasadena, CA 91124

Morrison-Knudsen
Two Morrison-Knudsen Plaza
P.O. Box 7808
Boise, ID 83729

Braddock, Dunn & McDonald
Alburquerque, Nm
(Vacuum Cryogenics Controls)

Urbahn/Lynn Associates
300 Park Avenue, South
New York, NY 10010
(Architects)

Joseph R. Loring CO.
(Engineers)

Rutherford & Chekene
(Geotechnical)

James Wilton
Jacobs Associates
500 Sansome
San Francisco, CA

Professor Garniss Curtis
Department of Geology & Geophysics
499 Earth Sciences Building
University of California
Berkeley, CA 94720

Jose Garcia, President
Sol-Arc CO.
2040 Addison Street
Berkeley, CA

Philip Banta
UC Berkeley

Charles J. Nafie, Jr.
Boston, MA
(Planner)

Howard, Needles, Tammer & Bergendoff
9200 Ward Parkway
P.O. Box 299
Kansas City, MO 64141

Sverdrup/Jacobs Jt. Venture
801 North Eleventh Street
St. Louis, MO 63101

Sverdrup & Parcel Assoc., Inc.
417 Montgomery Street
San Francisco, CA

Jacobs Engineering Group, Inc.
251 So. Lake Avenue
Pasadena, CA 91101

Princeton Plasma Physics Laboratory
Princeton University
P.O. Box 451
Princeton, NJ 08544

Fluor Engineers, Inc.
Advanced Technology Division (ATD)
333 Michelson Drive
Irvine, CA 92730

Daniel International

Fenix & Scisson, Inc.
1401 So. Boulder
Tulsa, OK 74119

Los Alamos Technical Associates
Los Alamos, NM

URS/John A. Blume & Associates Engineers
130 Jessie
San Francisco, CA

EMF Group-Jt. Venture

Engineering Decision Analysis Corp.

MBT Associates

Forell/Elsesser Engineers, Inc.
539 Bryant Street
San Francisco, CA 94107-1270

Dames & Moore
445 So. Figueroa Street, Ste 3500
Los Angeles, CA 90071
(Geotech & EIS)

Lachel Hansen Associates
Golden, CO
(Tunnels)

George Nolte Associates
(Waste Treatment)

Gayner Engineers
821 Howard Street
San Francisco, CA 94103
(Mechanical Engineering)

The Engineering Enterprise
620 Bancroft Way
Berkeley, CA
(Electrical)

YEI
1485 Bayshore Blvd.
San Francisco, CA
(Substations)

Gus Atkinson
(Construction Management)

SWA
(Sasaki, Walker, Assoc.)
Sasaki Associates, Inc.
64 Pleasant Street
Watertown, MA 02172
(Planning and Landscaping)

DKS, Inc.
319-11th Street
San Francisco, CA
(Traffic Consultants)

Charles M. Salter Associates, Inc.
350 Pacific Avenue
San Francisco, CA 94111
(Acoustics)

Marshall Associates
(Food Services)

RTK-Jt. Venture
1800 Harrison Street
Oakland, CA 94623-2321

Raymond Kaiser Engineers
300 Lakeside Drive
Oakland, CA

Tudor Engineering CO.
149 New Montgomery Street
San Francisco, CA 94105

Keller & Gannon-Knight
1453 Mission Street
San Francisco, CA 94103

Wm. L. Pereira Associates
27 Sutter Street
San Francisco, CA
(Architects)

Earth Technical Corp.
(Geotechnical)

J. Warren & Associates
1800 North Charles Street, Ste 54
Baltimore, MD 21201
(Roads)

EBASCO-Jt. Venture

EBASCO Services, Inc.
Two World Trade Center
New York, NY 10048
(Sub. of Enserch Corp.)

Losinger
Switzerland

Westinghouse Elec. Corp.
Westinghouse Bds Gtwy Center
Pittsburgh, PA 15222

Rockwell Corp.
600 Grant Street
Pittsburgh, PA 15219

Stone & Webster Engineering Corp.
245 Summer Street
Boston, MA 02107

Amman & Whitney
Two World Trade Center
New York, NY 10048

Peter Tarkoy, Consultant
(Tunnels)

John Erlewine, Consultant
(Former G.M.--CH AEC Office)

Brown & Root Development, Inc.
P.O. Box 3012
Naperville, IL 60566
(Subs. of Halliburton CO.)

Alvord, Burdick & Howson
20 N. Wacker
Chicago, IL 60606
(Tunnels)

STS Consultants, Inc.
(Soil Test)

Chicago Bridge & Iron CO.
800 Jorie Blvd.
Hinsdale, IL 60521
(Cryogenics & Vacuum)

NUS Corporation
910 Clopper Road
Gaithersberg, MD 20760
(Environmental)

Black & Veatch Engineers-Architects, Jt. Venture
1500 Meadow Lake Parkway
Kansas City, MO 64114

Marshall & Brown, Inc.
Architects

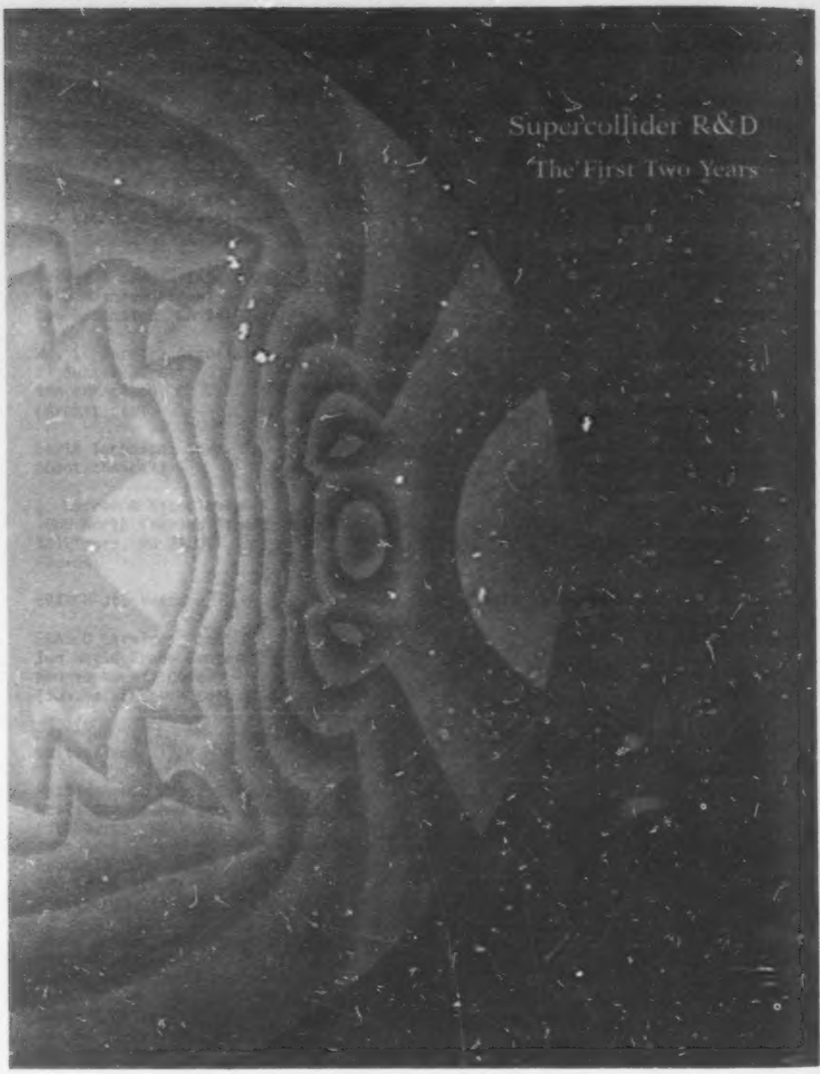
Cryogenic Consultants, Inc.
1176 North Irving Street
Allentown, PA

Motor Columbus Associates
Switzerland
(Tunneling)

Boude C. Moore
Coronado, CA
(Vacuum)

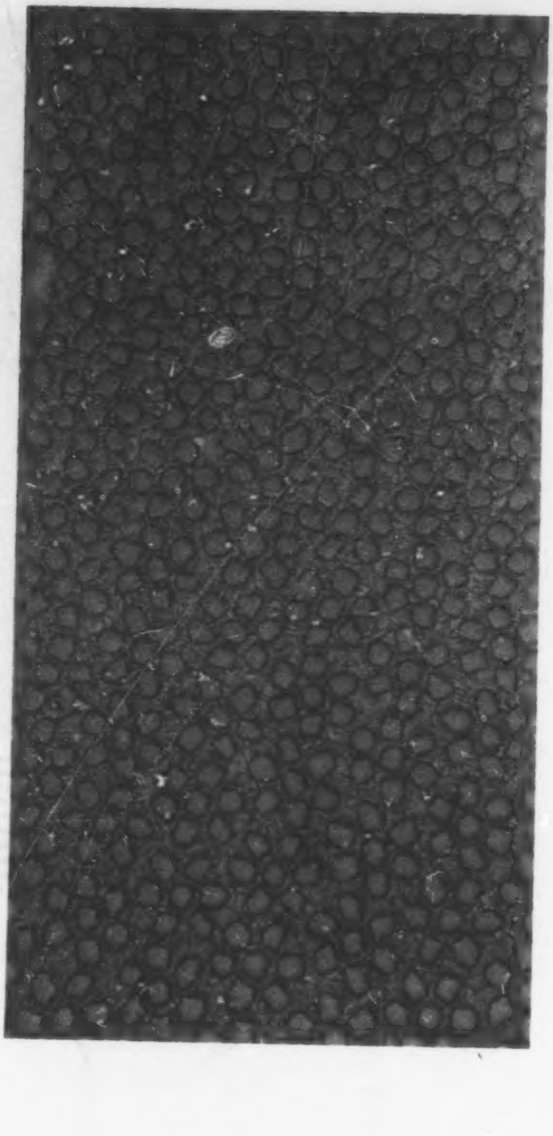
Dames & Moore
Los Angeles
(Geotechnical)

APPENDIX 16



Supercollider R&D

The First Two Years



COVER: Magnetic field intensities in a cross section of a Superconducting Supercollider Design D dipole magnet coil. A spectrum of 512 colors represents field strengths, with the blue and white areas indicating the high field (6.6 Tesla) in the beam pipe where protons will orbit at a velocity near the speed of light. Interpolation between 15,000 calculated points in the computer program allows more than 250,000 points to be displayed in one quadrant, which is then reproduced photographically to portray the symmetrical cross section. (Courtesy of Lawrence Berkeley Laboratory)

RIGHT: Portion of a cross section, enlarged approximately 2000 times, through a single strand of high-current-density superconducting magnet wire developed in the SSC R&D program. The hexagonal floret pattern is produced in a double extrusion process whereby seven rods of niobium-titanium alloy in a copper matrix are first extruded to 30 feet. Then these units are stacked in an 858-rod billet and extruded once more to produce 48 miles of wire with 6006 very fine filaments. (Courtesy of Intermagnetics General Corporation)

Supercollider R&D

The First Two Years

UNIVERSITIES
RESEARCH
ASSOCIATION

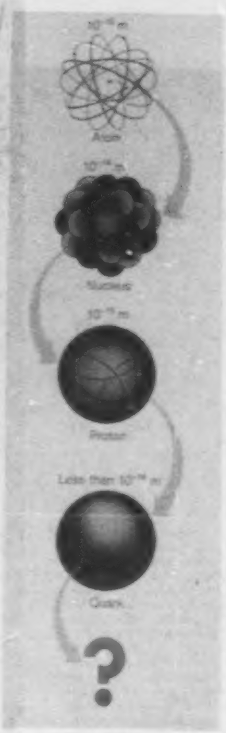
WASHINGTON D.C.

DECEMBER 1985

The SSC Concept

The continuous advance of particle research during the past twenty-five years has allowed physicists to develop a strong working hypothesis about the fundamental laws of nature. This Standard Model is based on a theory of elementary subatomic particles—the quarks and leptons—which interact through forces carried by other elementary constituents—the gauge particles. But while the Standard Model provides a powerful understanding of natural phenomena, it fails to predict some of the basic patterns in nature. It relies too heavily on empirical arguments for some of its explanations and applies to a limited energy domain.

The further exploration of the realm of the infinitesimal requires a new research instrument of immense size and unprecedented energy. In 1983 the American particle physics community strongly recommended building a collider of this huge scale. The Superconducting Supercollider, or SSC, will be twenty times more powerful



Descent into the atom, where particle physics discoveries in recent decades have brought increasing knowledge of the elementary structure of matter. Even quarks, the smallest building blocks now known, may be composite structures of smaller elements. Experiments with the Supercollider are expected to shed light on questions such as these which concern the realm of the infinitesimal.

than the state-of-the-art Tevatron at Fermilab. It will enable scientists to peer deeper than ever before into the subatomic world, where discoveries in the unexplored areas of particle physics will extend the boundaries of knowledge about matter in the universe.

The SSC will be the world's largest scientific instrument and most powerful particle accelerator. Its front-end injector system alone will match the size of the entire Tevatron, and its main accelerator ring will be some 60 miles in circumference. The design of the main ring utilizes the concept of two proton beams traveling in opposite directions in a tunnel and ntersecting in six underground hambers where particle collisions an be studied in detail. Thousands of superconducting magnets ill steer and focus the beams as hey circulate and attain a very igh energy and a velocity essentially equal to the speed of light. he success of the Tevatron demnstrates that machines of this ype can be made to work, and ork well.

While the SSC will rely on the asic design principles of the Tev-tron, it will employ even more dvanced superconducting tech-ology, including significant im-rovements in superconducting aterials, to create beam energies s great as 20 trillion electron olts, or 20 TeV. In this realm omplex new phenomena are ex-ected to emerge, enabling scien-sts to reach beyond the realm of alidity of the Standard Model d attain a deeper understanding the nature of matter.

The R&D Program

The success of the SSC machine will depend on the smooth operation of its complex technical components as an integral system. Extending the technology of the Tevatron to meet the system design requirements of the SSC entails an R&D effort of considerable scope.

The U.S. Department of Energy initiated preliminary R&D for the Supercollider in the fall of 1983 and sponsored a Reference Designs Study that was completed in May of 1984. The study concluded that the technology for a 20-TeV collider was essentially in hand and that the machine could be built for a well-determined cost after further R&D. The aims of the R&D effort were to be the verification of assumptions made in the study and the optimization of existing technology.

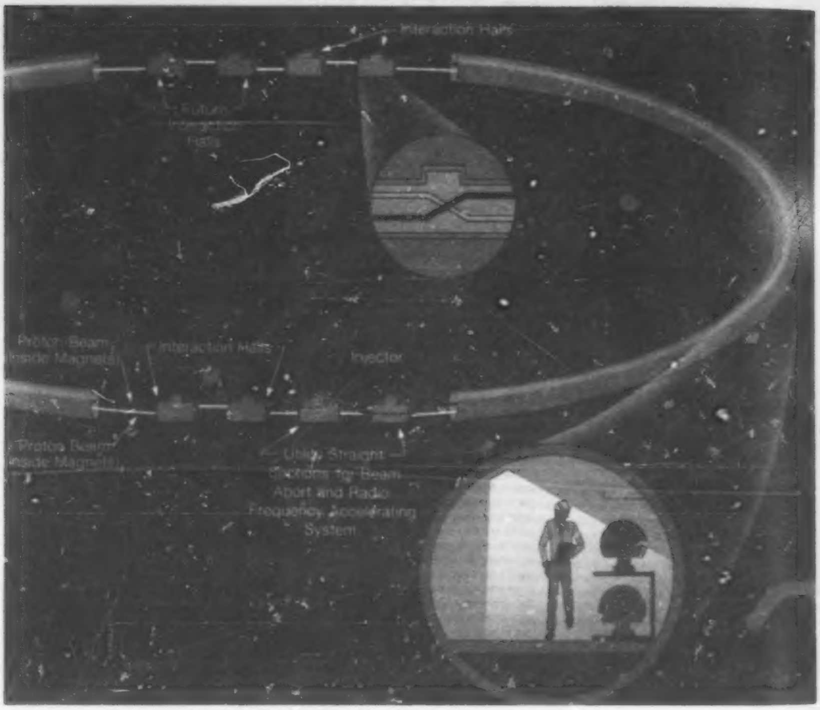
In the spring of 1984, DOE contracted with Universities Research Association, a consortium of 56 leading research universities, to direct and coordinate the R&D phase of the SSC program. The association established a Central Design Group to lead the national R&D effort and located it at Lawrence Berkeley Laboratory. The work managed by the CDG has been carried out by Fermilab,

Proposed layout for the SSC facility, with interaction halls clustered on the two gently-curved sides of a ring shaped like a racetrack. In this perspective the nearer cluster incorporates the front-end injector, radio-frequency accelerating system, beam abort, and two of six interaction halls where counter-circulating proton beams will intersect to produce particle collisions. The farther cluster adds four more interaction halls, two of which will be reserved for development after research operations begin. The schematic enlargement inside the ring shows the intersection of the two beams in an interaction hall; the cross section to the right shows the position of the two superconducting magnet rings in the tunnel space.

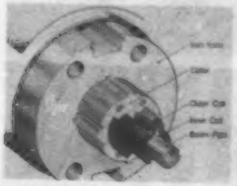
Brookhaven National Laboratory, Lawrence Berkeley Laboratory, the Texas Accelerator Center, and several other laboratories, universities, and industrial concerns.

The technological progress of the SSC R&D effort to date has been substantial. Investigators have developed magnet and systems technology that meets, and in some areas exceeds, the expectations of the Reference Designs Study. A major milestone in the program has been reached—the selection of the Design D magnet style as the basis for the SSC conceptual design. Most importantly, the Supercollider researchers have demonstrated that a 20-TeV collider can be built and operated within well-defined costs.

The technology of the superconducting magnets has been the main focus of the R&D program


Interaction Halls
Future Interaction Halls
Proton Beam
Inside Magnets)
Interaction Halls
Injector
Proton Beam
nside Magnets)
Utility Straight Sections for Beam Abort and Radio Frequency Accelerating System

during the past two years. Investigators have looked closely at several magnet designs, advanced the technology of superconducting magnet wire, and studied the magnet cooling system. The results of this research have been most promising: excellent magnetic field quality has been achieved with reliability, the current-carrying capacity of the wire has increased dramatically, and the cooling power estimates of the Reference Designs Study have been verified experimentally. These are key steps in defining the conceptual design for the SSC, since the magnet system is the most complex technical component of the machine. The research effort to date has provided confirmation of the design calculations and technical assumptions of the Reference Designs Study.

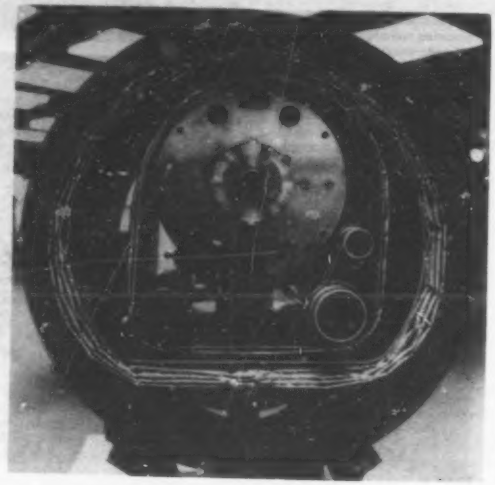


The Superconducting Magnets

During the past two years the Supercollider R&D program has concentrated on the large superconducting magnets that curve the orbits of the proton beams as they circulate within the main accelerator ring. It is generally agreed that the results of this R&D effort will allow considerable cost savings through improvements in the magnet materials and system subcomponents.

A concerted research effort by the U.S. high energy physics community in recent years has led to a clear understanding of the basic technology of the accelerator superconducting magnet. The Tevatron, with a circumference of 3.9 miles, contains about 1,000 large superconducting magnets of various types. Operational experience with the Tevatron, together with a growing knowledge of superconducting magnet behavior, makes it possible to predict performance characteristics for the SSC with great reliability.

The SSC magnet system is a complex of technical components that must function harmoniously to control the proton beams as they travel through the main accelerator ring. Almost all the magnets in the main ring will use coils wound from superconducting cable to transmit electric current and create the magnetic field that



ABOVE: Cutaway perspective of the Design D single-beam superconducting magnet chosen by the SSC Design Group as the style for the Supercollider. In this design each of the two counter-circulating proton beams is enclosed in a separate ring of magnets and cryostats.

RIGHT: Preliminary R&D model of the Design D magnet, built to demonstrate how the components fit together inside the cryostat. The yoked magnet assembly is enclosed (moving outward) inside an inner shield, several layers of superinsulation, and an external vacuum vessel. (Courtesy of Fermi National Accelerator Laboratory) steers the beams. A radio frequency system will accelerate the beams through vacuum pipes located in the center of the magnets. The magnet coils will be encased in low-temperature cryostats cooled with liquid helium and operated at a temperature of only 4.3 degrees above absolute zero, or 4.3 K.

During the past two years, five different magnet styles were investigated in detail at laboratories around the country. The overall quality of accelerator magnets is judged largely by the field uniformity, since an extremely uniform field is necessary to control the proton beam. The SSC research magnets have demonstrated that the necessary field uniformity can be readily achieved. Furthermore, experience with the Tevatron shows that accurate magnets can be manufactured in large quantities. The R&D effort has demonstrated that manufacturing techniques are now well understood, and the predicted field strength can be reached.

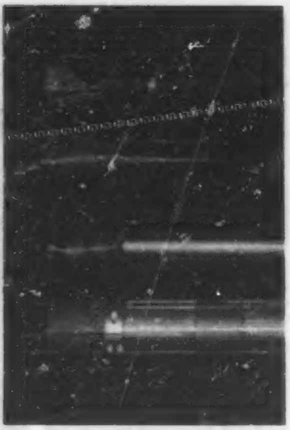
Research on the Design A high-field magnet at Brookhaven National Laboratory and Lawrence Berkeley Laboratory produced good results, with field strength and quality meeting all predictions. Work on the Design B high-field magnet at Fermilab was also promising. These two magnet styles provided data for the design of the optimized Design D magnet, which combines their best features.

At LBL six 1-meter Design D magnets were constructed with extensive instrumentation to measure their behavior when first powered as well as their field quality. At Brookhaven six 4.5-m models were built to demonstrate reproducibility. All the Design D research magnets reached a field strength of 6.6 Tesla or higher, with prompt achievement of acceptable performance levels and excellent uniformity of field.

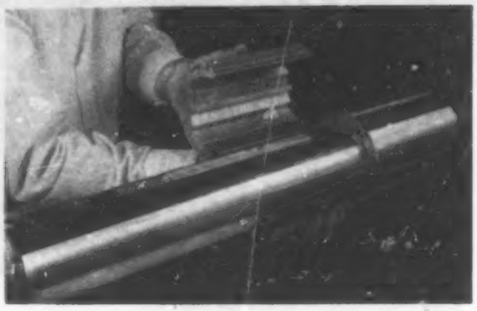
Construction of a Design A research magnet, an early candidate for the SSC. The design featured both of the proton beam pipes enclosed inside a single yoke, a so-called two-in-one style. The research model pictured here uses a demountable bolted yoke assembly for the purpose of laboratory study of magnet performance. (Courtesy of Brookhaven National Laboratory)

BUILDING THE DESIGN D SUPERCONDUCTING MAGNETS

Four stages in assembling a 1-m Design D magnet. The top view shows a fully wound magnet coil with loose cable ends ready for trimming, and the second view shows the magnet wrapped with transparent insulation. The first collar pack has been applied in the third view, and a complete set of five collar packs completes the basic magnet core in the bottom view. (Courtesy of Lawrence Berkeley Laboratory)



Close-up of the end of a 1-m magnet still on the mandrel used to support it during assembly. The two layers of coils are clearly visible. The inner coil is wound from cable comprising 23 strands of superconducting wire, the outer coil from cable comprising 30 strands. This intermediate Design D magnet has a flared end, but the most recent magnets have a flush, cylindrical end for ease of mass production. (Courtesy of Lawrence Berkeley Laboratory)



Applying a collar pack to an insulated 1-m magnet before mechanical pressing around the coil assembly. The collared style of magnet was borrowed from the preliminary Design B magnet and adapted to the Design D specifications. The collars ensure that the coils will be held firmly in place when the magnet is powered to the design field of 6.6 Tesla. (Courtesy of Lawrence Berkeley Laboratory)

Fully assembled magnet undergoing preparation for testing in a liquid helium cryostat. The beam pipe, visible at left, is surrounded by superconducting cable coils, collars, an iron yoke, and a stainless steel outer vessel, which is being aligned for welding. (Courtesy of Brookhaven National Laboratory)

Collaring a 4.5-m magnet with a hydraulic collaring press. At this stage in assembly a locking key is being installed to hold the collar components together after they have been applied to the magnet. (Courtesy of Brookhaven National Laboratory)

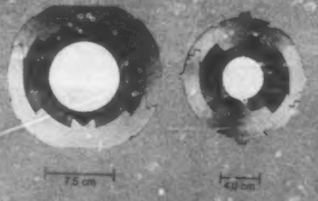
Beam Stability and Aperture

An important factor in the cost of the SSC magnets is the physical size of their coils. Minimizing the coil size will result in a substantial reduction in the amount of costly superconductor cable required to power the magnets and the other materials used in their manufacture. The cost of the materials for the magnets becomes a major factor in the cost of the Supercollider when the great number of its magnets is taken into account, and a significant R&D effort is warranted to reduce the coil size.

The main feature in determining the coil size is the behavior of the proton beam as it travels through the magnetic field created by the coils. If too small a size is chosen the magnetic field will have inadequate quality, and this will lead to instability in the motion of the beam particles. It is extremely important to choose a coil size that leaves sufficient room for stable particle motion while minimizing the cost of the magnets.

Determining the minimum aperture size for the beam requirements of the SSC has been a focal point of effort during the past year, and the preliminary results of the research are promising. An algorithm for evaluating the field quality of the magnets has been developed, and initial calculations indicate that a 2-cm-diameter stable region for the beam can be maintained with a coil size of only 4-cm inner diameter—substantially smaller than the 7.5-cm diameter of the Tevatron coils.

Some features of the beam algorithm can be readily tested at the Tevatron, and the preliminary trials have already yielded encouraging results. Research along this line will continue in an effort to assess and improve the algorithm. In particular, the effect of moving the beam off center will be measured to check the calculations. The results are expected to confirm that the low-cost 4.0-cm bore for the Supercollider magnets will meet the requirements for reliable SSC operation.



Cross section through a collared Tevatron magnet, left, and a collared Supercollider Design D magnet, right. The cable coils are visible here as curved elements stacked along the central beam pipe. The inner diameter of the coils for the Supercollider will be about half that of the coils for the Tevatron, resulting in considerable savings in magnet construction materials. (Courtesy of Fermi National Accelerator Laboratory)

Most of the research on the Design C lower-field magnet and a variant, C*, was carried out at the Texas Accelerator Center near Houston. This design is quite compact and requires less iron and superconductor than the high-field designs. Eight 1-m and two 7-m magnets were built and tested; two 28-m magnets are being assembled to investigate the problems of manufacturing very long magnets.

The results of the Supercollider R&D program on magnet design are very encouraging. Several different magnet styles have been tested with working models, and they have displayed excellent field characteristics. The selection of the Design D magnet as the style for further development will allow the conceptual design of the SSC to move forward according to schedule during the first half of 1986.

Close-up of the end of a preliminary Design C two-in-one, low-field superconducting magnet. The vertical arrangement of the two beam pipes and the compact structure of the magnet are distinctive characteristics of the design. Because the iron yoke, and not the magnet coils, produces most of the magnetic field, less superconducting cable is needed to build the magnets. (Courtesy of Texas Accelerator Center)

Instrumented magnet assembly undergoing testing to check pressure gauges before installation in an iron yoke.

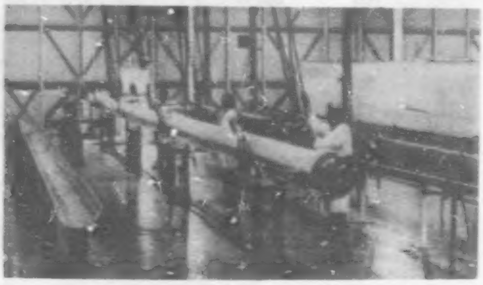
Pressure gauges installed in the bottom part of a collar pack, resting on a testing block. The instrumented top part of the pack is shown in the foreground. The gauges sense pressure during collaring and operation, as well as other magnet stress parameters, to determine what pressures will result in the most efficient magnets. (Courtesy of Lawrence Berkeley Laboratory)

Selection of the SSC Magnet Style

In August of 1985, after the R&D program had produced a substantial body of information on the five candidate magnet styles, the SSC Magnet Selection Advisory Panel unanimously recommended that the Design D magnet be chosen for the Supercollider. The director of the Central Design Group accepted this recommendation.

The selection of the Supercollider magnet style represents the most significant milestone in the R&D effort to date. The magnet selection process was developed in consultation with the concerned scientific and technical community. The basic issues included relative capital cost, workability of the design, complexity of the overall magnet system, operational complexity, flexibility, impact on construction scheduling, further R&D requirements, and accelerator physics questions. Initially, a Technical Magnet Review Panel was convened to review the status of the R&D program and recommend modifications in the program in order to ensure that enough technical information would be available to choose a magnet by the end of the summer of 1985. The CDG also set up three special task forces to collect and evaluate specialized information—the Aperture Task Force, Cost Comparison Task Force, and Operations and Commissioning Task Force.

The selection panel based their recommendation on the reports of these groups and on presentations of the R&D results by the scientists and engineers involved. In its deliberations the Magnet Selection Advisory Panel considered all five of the magnets that had been studied. Early in the process the panel narrowed the choice to two styles, Design C and Design D. Upon further consideration, the panel and its industrial consultants unanimously recommended the D magnet.



Twenty-eight-meter Design C magnet ready for assembly inside a vacuum vessel shown at left. Very long magnet designs are being investigated in the R&D program to minimize installation and interconnection requirements inside the Supercollider tunnel. (Courtesy of General Dynamics Corporation and Texas Accelerator Center)

The panel's decision rested primarily on three factors. First, the characteristics of the D magnet are well understood because of its similarity to the Tevatron magnet, and thus its cost and production schedule can be estimated with accuracy. Second, the operation of a Supercollider based on Design D will be less expensive and easier than one based on Design C. Finally, the overall cost of a collider built with Design D magnets is estimated to be somewhat less than one built with Design C magnets. In short, the panel was convinced that the Design D magnet style holds the greatest promise of success at the least cost.

The next step is to produce a conceptual design based on the chosen magnet type and the other results of the research, development, and testing program. All of the R&D teams who were involved in the research leading to the magnet decision will continue to work on optimizing the overall magnet design and related components of the Supercollider. Their efforts will provide the information necessary to produce a conceptual design report by April of 1986.

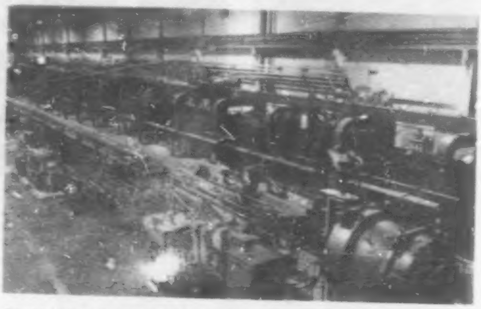
Sample of superconducting wire cable produced in the Supercollider R&D program. The cable shown here comprises 30 strands of superconducting wire, each of which contains thousands of very fine filaments of superconductor alloy embedded in a copper matrix. The copper has been etched away from the filaments, and the filaments have been frayed so that they can be seen easily. (Courtesy of Lawrence Berkeley Laboratory)

Superconducting Wire R&D

Research on the quality and manufacturing technology of superconducting wire for the cable of the SSC magnet coils has produced a significant improvement in the current-carrying capacity of the wire. Superconductor R&D for the Supercollider has advanced the state of the art of superconducting wire manufacturing in the United States and improved the competitiveness of American companies in the world superconductor market. In parallel, significant advances have also been achieved by European and Japanese industry.

Superconducting wire cable forms the heart of the superconducting magnet and is the key element in its success. To produce the cable several thousand ⅛-inch rods of superconductor alloy are first stacked into billets within a copper matrix. The billets, measuring up to a foot in diameter and 2.5 feet in length, are next drawn into wire, and the rods become fine filaments of superconductor within the wire. The wire is then wound into flat cable of either 23 or 30 strands, depending on its use in constructing the magnet coils for the SSC.

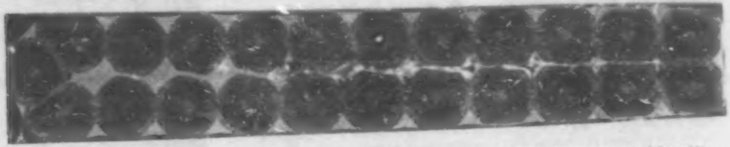
High-performance superconducting wire can lead to significant savings by reducing the amount of costly alloy required for the magnets. Recent research has pushed the current-carrying capacity of the wire well beyond what was considered possible a few years ago. Improvements have been made in the quality of the niobium-titanium (NbTi) alloy used for the wire, in the preparation for drawing and the drawing process



Drawbench for pulling billets of superconductor alloy rods in a copper matrix into superconducting wire. With a length of 200 feet and a pulling force of 150,000 pounds, this bench is among the most powerful in the world. It allows the economical fabrication of wire in one step by eliminating the necessity of cutting the wire down for continuous redrawing. (Courtesy of Intermagnetics General Corporation) itself, and in cable production.

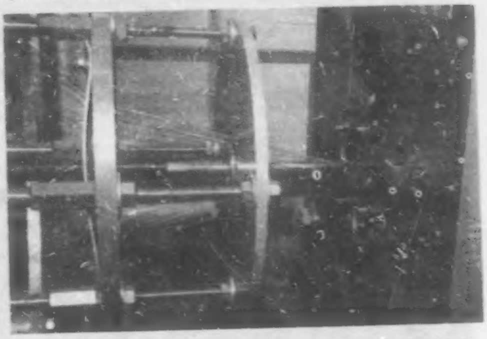
Research at the University of Wisconsin has shown that NbTi alloy rods used in the past to make the billets were actually somewhat inhomogeneous on a microscopic level, varying as much as 5% from the ideal 45/55% mix. A joint effort among DOE, industry, and academia produced new techniques for improving this superconductor material. A major breakthrough was the development of a high-homogeneity alloy that is now available for general commercial use.

Studies of the wire drawing process were also performed at the University of Wisconsin, with an immediate practical result. Compared with current densities around 1800 amperes per square millimeter (1800 A/mm^2) for the Tevatron wire, the first experi-



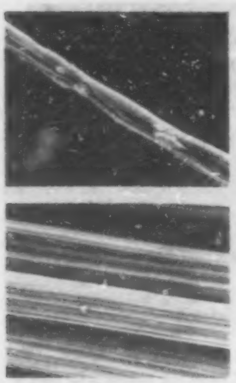
Close-up of a cross section of 23-strand superconducting wire cable for the Supercollider magnets. The actual width of the cable, left to right, is only 0.366 inches; the average diameter of a single wire is 0.0318 inches. The individual wires have been misshapen somewhat, the natural result of the cabling process; but the structure of each wire, with its thousands of superconductor filaments, is plainly visible. (Courtesy of Lawrence Berkeley Laboratory)

Aluminum drum for spools of wire which is being wound into cable for the SSC magnets. The drum, newly designed for the Supercollider R&D program, can feed up to 36 strands of wire at once into the cabling machine lathe. (Courtesy of Lawrence Berkeley Laboratory)



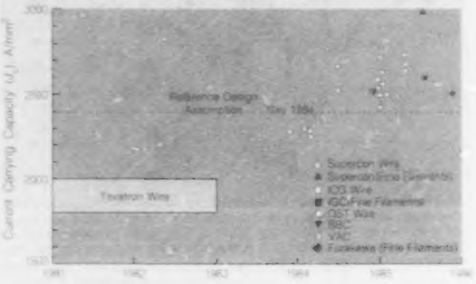
Close-up of the wire-guide section of the cabling machine, visible at the far right in the preceding photograph. The individual wires are brought together, drawn through the guide and twisted on a mandrel before being fed into the turkshead, right, for flattening. When the cable has been formed it is bound with insulating tape and wound onto large spools for shipment to magnet construction facilities. (Courtesy of Lawrence Berkeley Laboratory) ments with new technology produced an average current density of about 2600 A/mm². This improvement is substantially greater than the goal of 2400 A/mm² set in the Reference Designs Study, and researchers now predict a density of at least 2700–3000 A/mm² when industry begins large scale mass production of the wire.

New wire cable designs and improved procedures for winding the wire into cables were also developed at laboratory facilities and transferred to industrial firms. The cable now meets the rigorous specifications for winding into coils that can achieve the desired field strength of 6.6 T. The final product of the R&D program in this area, then, is relatively flexible cable made of superconducting wire with very homogeneous filaments. Through technology transfer to industry, the entire wire manufacturing process has seen considerable improvement and the reproducibility of the process under manufacturing conditions has been amply demonstrated.



Scanning electron microscope micrographs reveal dramatic improvement in the quality of superconducting wire filaments. The knobby, twisted filament in the top figure is from wire developed for the Tevatron, with a current-carrying capacity of 1800 A/mm². Research conducted in cooperation with the University of Wisconsin resulted in an increase to 2800 A/mm² (bottom figure). (Courtesy of Brookhaven National Laboratory and Lawrence Berkeley Laboratory)

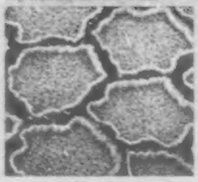
Improvement in the quality of superconducting wire developed in the R&D program, from the Tevatron wire to the most recent samples.



Fine Filaments: A Possibility for Further Cost Savings

The diameter of the NbTi filaments in the superconducting wire influences the complexity and cost of the SSC magnet system. Conductor-dominated magnets exhibit some field inhomogeneities at low fields due to magnetization currents in the cable. This effect must be compensated with correction coils. If the filaments can be made fine enough, however, the magnetization currents diminish to the point where the correction components can be simplified or eliminated altogether—resulting in appreciable cost savings.

The wire manufacturing process starts with a large billet of NbTi alloy rods in a copper matrix that is then drawn into superconducting wire. Producing very fine filaments requires stacking enough NbTi alloy rods in the billets to produce a filament diameter of only 2–3 micrometers after drawing. Two different methods have shown very good results, and one early lot of commercially produced material with 5-micrometer filaments exhibited a current carrying capacity of 3000 A/mm².



Scanning electron microscope micrograph of superconducting wire filaments with a diameter of 2.5 micrometers and very even spacing. The copper of the matrix (dark area) has been etched away to expose a niobium treatment layer which prevents interaction of the NbTi with the copper. This treatment reduces damage to the filaments during processing. (Courtesy of Supercon, Incorporated)

Systems Engineering: Cryogenics and Synchrotron Radiation

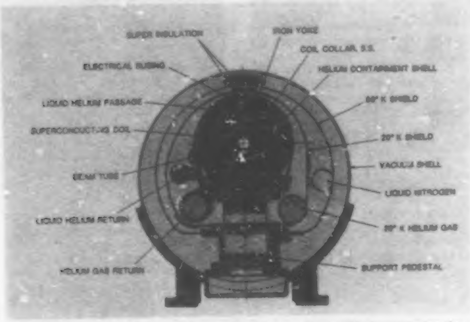
A critical measure of success of the Supercollider will be its overall availability for particle physics experiments. A major investigation into the development of reliable, cost-effective systems components for the machine was begun as part of the SSC research effort during the past year.

The size and complexity of the SSC cryogenic (cooling) plant have made it a main focus of the systems engineering research program. The plant will consist of several complete refrigeration and distribution systems to cycle liquid helium coolant through the superconducting magnets and keep them at the prescribed operating temperature of 4.3 K.

A key aspect of the cryogenics research has been the reduction of heat leakage into the magnet cryostats by optimizing the placement of insulation and the support post configuration. Models of one cryostat design have confirmed the Reference Designs Study estimate that heat leakage can be reduced by a factor of five compared with the Tevatron figure. Measurements of leakage have been made in a 12-m model cryostat, and the thermal insulating blankets and folded support posts in the model have proved very effective. The combined heat leakage to the parts of the model with temperatures of 10 K and 4 K was only 0.25 W/m, commensurate with the estimates of the Reference Designs Study.

During the past year significant progress has also been made in understanding the potential effects of synchrotron radiation on the SSC vacuum system. Synchrotron radiation has been a familiar phenomenon in the operation of electron storage rings, but not in proton machines. The SSC will be the first proton accelerator with energy high enough that the protons will emit a significant number of energetic photons which might affect the beam lifetime. The emitted photons desorb gas molecules from the beam pipe walls, building pressure within the pipe. If allowed to accumulate, these molecules could shorten the beam lifetime.

Whereas the warm vacuum pipes of electron storage rings permit the removal of desorbed molecules through conventional distributed pumping around the ring, the

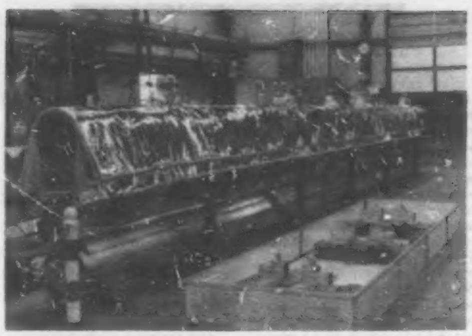


Cross section of the SSC Design D magnet and cryostat assembly, incorporating the latest design features. Multiple layers of superinsulation and an innovative post support system will decrease heat leakage into the cryostat. Recent investigations indicate that leakage will be reduced by at least a factor of five when compared with the performance of the Tevatron cryostat.

Newly-designed support post for the Supercollider magnet and cryostat assembly. The post, shown from the underside, is mounted into a Dewar testing apparatus in preparation for the measurement of heat leakage. Instrumentation wires are visible around the necks of the post assembly. (Courtesy of Fermi National Accelerator Laboratory) cold pipe of the SSC makes this solution impractical. Furthermore, since the cold pipe acts as an effective vacuum pump by freezing gas molecules to its surfaces, photons could do more damage by desorbing those molecules.

The CDG has mounted two experiments to learn more about the desorption effects of synchrotron radiation. Both were conducted with the vacuum ultraviolet ring at the National Synchrotron Light Source at Brookhaven National Laboratory. The first experiment used an aluminum pipe at room temperature to verify the experimental method; the results showed very good agreement with previous data on the rate of desorption. The second experiment used a stainless steel pipe cooled to liquid helium temperature. The preliminary results from the second experiment demonstrate that the effects of photodesorption are observable, but that they should have no significant effect on the beam lifetime.

Further experiments with cold copper pipes and strong magnetic fields are scheduled at Brookhaven for the next phase of R&D. In addition, Japanese investigators are collaborating with U.S. researchers to conduct similar experiments in Japan with cold aluminum pipes.



Multi-layer superinsulation being installed around a cold mass designed to simulate a type D magnet. The assembly is being prepared for the measurement of heat leakage (Courtesy of Fermi National Accelerator Laboratory)

Vacuum ultraviolet ring at the National Synchrotron Light Source in Brookhaven, Long Island. Two experiments were mounted at this facility to learn more about the desorption effects of synchrotron radiation in the SSC. Further testing will explore the effects of cold beam pipes and strong magnetic fields on beam integrity in the Supercollider (Courtesy of Brookhaven National Laboratory)

Siting Criteria and Tunnel

After the superconducting magnets, the tunnel that houses the SSC main ring is the most costly component of the facility. The tunnel warrants a significant investigative effort to understand and minimize construction costs. Since a definitive tunnel cost estimate will depend on the selection of a specific site, R&D during the past year has emphasized follow-up studies of the Reference Designs Study cost estimates, the development of siting criteria, and the collection of information on tunneling technology to develop a future construction R&D plan.

Creating a detailed set of siting parameters for the Supercollider was a major part of the R&D effort during the past year. The background description of the required site was based on the work done for the Reference Designs Study in 1984. The central feature of the facility is a tunnel of 60 miles circumference at a minimum depth of 20 feet below the surface. An injector complex with an accelerator ring several miles in circumference is situated tangential to the main ring. At six points about the main ring are collision halls—large underground chambers where the proton beams will intersect and detectors will record the collision events. A research campus near the injector complex will provide facilities for 3,000 scientists, engineers, and technical workers.

Based on these major components of the facility, a Siting Parameters Document was prepared to provide the Department of Energy with a set of suggested criteria to be used in evaluating potential sites for the SSC. The report describes needed features of a future site and details information which should be provided about potential sites. It represents an important step toward an eventual evaluation of potential SSC sites by DOE.

In spring of 1985 an architectural and engineering (A/E) group of companies was selected to support the R&D effort in developing a set of conceptual designs for the conventional structures. This joint venture is also evaluating typical tunneling methods and costs for construction in soft ground, soft rock, and hard rock. During the next year the A/E group will provide a conventional facilities design for the 1986 SSC cost estimate. Besides underground and above-ground systems, the joint venture will be involved in examining safety, utility distribution and monitoring, and other factors in the overall design of the Supercollider facility.

Cross section of the SSC tunnel, measuring approximately ten feet in internal diameter in the present design. The interior space is divided roughly into thirds, with the magnets at the right, space for the passage of people and magnets in the middle, and a transportation vehicle at the left. Utilities are suspended in trays at the crown of the tunnel. A program has been established to assess the cost alternatives for construction of the tunnel and other conventional physical facilities for the Supercollider and to propose a conceptual design for the entire facility during 1986.

Suggested Siting Criteria for the SSC

Setting	Space for a ring of 60 miles circumference; a site for a machine which is level or with a tilt <1°; surface area up to 11,000 acres
Environmental	Compliance with NEPA standards; baseline data to address environmental issues
Geology and Tunneling	Long, uniform material, extensively characterized rock; avoidance of active faults; good wall stability; avoidance of unconsolidated soils with ground water; data on seismic activity
Community	Staff needs: housing, educational, cultural facilities; reasonable commuting times, major airport, all-weather roads; adequate industrial/construction resources
Utilities	Up to 2000 gal/min of water; up to 250 MW of electrical power, with separate feeds and fewer than two outages per year
Man-Made Disturbances	Avoidance of excessive noise and vibration
Cost and Schedule	Description of land costs, utility rates, willingness to offset costs to DOE

Toward a Final Supercollider Design

During the past two years a major R&D program has been conducted to investigate various alternatives for the basic components of the Superconducting Supercollider. This successful program has permitted the SSC Central Design Group to select the Design D high-field magnet for the collider and has verified the cost estimates and technical assumptions of the 1984 Reference Designs Study.

The fabrication and testing of several different styles of superconducting magnet confirm this technology as a mature, well-understood basis for the SSC machine. The field uniformity and field strength of the research magnets are excellent, and these achievements pave the way for the production of full-length prototype magnets and study of their performance during 1986. The quality and manufacturing characteristics of the superconducting wire, key factors in the cost of the magnets, have seen a major improvement thanks to a collaborative research effort with U.S. industry.

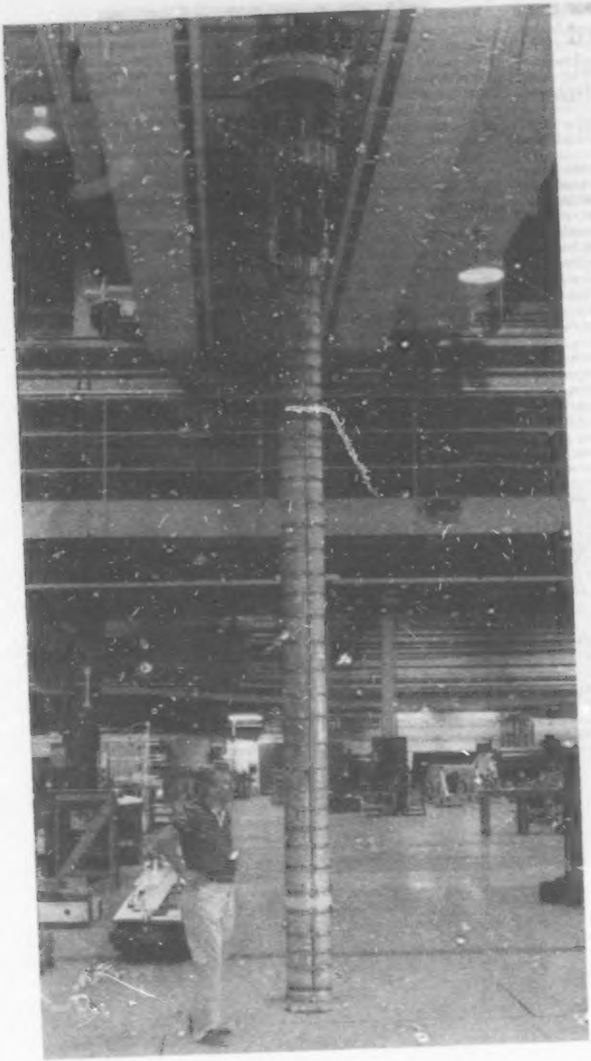
The systems aspects of the SSC have also undergone considerable development during the past year. The commissioning and performance characteristics of the various magnet styles have been analyzed, and the essential decisions have been made concerning the most practical and cost-effective design features. Heat leakage into the cooled SSC magnet system has been reduced by more than a factor of five compared with the Tevatron, and the effects of synchrotron radiation on the vacuum in the beam pipe are better understood. Specification of the properties of the proton beams and calculation of the resulting beam dynamics have allowed the inner diameter of the magnet coil to be reduced to 4 cm in the SSC, compared with 7.5 cm in the Tevatron. All of these achievements indicate that the Supercollider will cost considerably less to build and operate, on a relative scale, than the Tevatron.

During the coming year the SSC R&D program will continue investigations of superconducting magnet technology, systems engineering, and design and construction alternatives. Production of several full-size Design D magnets is underway in preparation for a systems test in October of 1986. A conceptual design report will be completed by April of 1986, and studies of the cost of constructing the conventional facilities under various geologic conditions will continue throughout the year. Further calculations and experiments are planned to study proton beam dynamics, the cryogenic system, and the effects of synchrotron radiation.

Progress on research and development for the SSC during the past two years has occurred through the combined efforts of the national laboratories, universities, and industry. The R&D effort is now focused on a particular magnet design aimed at providing an efficient, cost-effective scientific instrument to investigate the basic constituents of matter over smaller distances and at higher energies than ever before. Understanding the elementary building blocks of nature and spurring technological innovation in diverse fields through experiments with the SSC machine will be the eventual rewards of this R&D effort. The progress of the past two years gives every indication that the SSC will be fully capable of accomplishing these goals.

The Superconducting Supercollider R&D program is supported by the U.S. Department of Energy.

Universities Research Association, a consortium of 56 research universities, is responsible for carrying out the program, which is coordinated nationally by the SSC Central Design Group, located at Lawrence Berkeley Laboratory, Berkeley, California.



A 4.5-m Design D superconducting magnet, hoisted on end for lowering into a vertical cryostat. Metal bands clamp the outer iron yoke to the magnet core. The magnet will be submersed in a liquid helium bath to evaluate its performance under conditions similar to those predicted for operation of the SSC. (Courtesy of Brookhaven National Laboratory)